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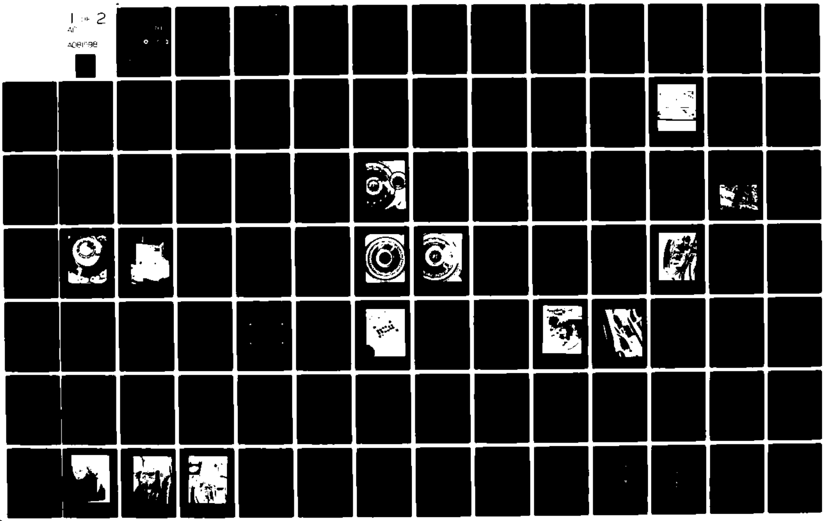

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FLIGHT TEST EVALUATION OF AIRBORNE TIRE PRESSURE INDICATING SYSTEMS

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DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

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16. Abstract

Results of flight testing of seven different cockpit tire pressure indicating systems are reported with an evaluation of each concept and recommendations for final in-service testing. Six prototype systems were evaluated on two McDonnell Douglas DC-10's between October 1978 and January 1979. One system was tested by an airline on a DC-9 and the results are included in the report as an appendix.

The systems evaluated included three analog tire pressure system concepts displaying actual tire pressure in the cockpit, two weight and balance systems measuring tire pressure indirectly via tire load and axle tilt, a go-no-go discrete pressure sensing system, and a wheel speed system that uses change in rolling radius to detect a low tire. A detailed test evaluation is included for each of the systems tested and comments on the general merits of each system type is included. A recommendation is made that each system be subjected to airline service test before entering fleet service.

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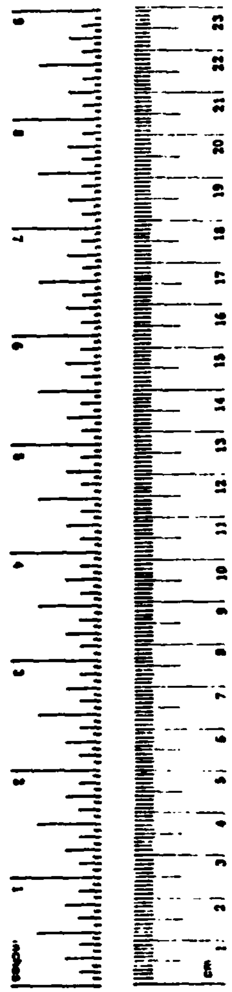
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

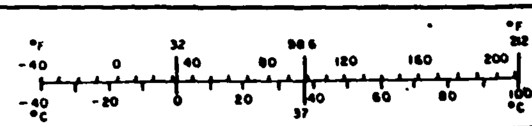
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This study was conducted and report prepared by the Douglas Aircraft Company, a Division of McDonnell Douglas Corporation, under a contract for the Federal Aviation Administration of the Department of Transportation. The effort is part of a study for the improvement of aircraft tire operational safety. Technical monitor for Federal Aviation Administration was Mr. Robert C. McGuire, FAA Program Manager, and Mr. Vincent G. Sanborn, NAFEC. The diligent efforts of the tire pressure indicating system manufacturers in support of this test program is acknowledged. Further, much of the data used in this report was derived from Douglas flight test and report summary supplied by the manufacturers.

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LIST OF ABBREVIATIONS

AC	Alternate Current
A/C	Aircraft
A/D	Analog to Digital (Data Conversion)
ALT	Altitude
A/S	Airspeed
ATR	Advanced Technical Requirements
BIT	Built-in-Test
°C	Degree Centigrade
c.g.	Center of Gravity
CPS	Cycle per Second
CPU	Central Processing Unit
D	Outside Free Diameter of Tire
DAC	Douglas Aircraft Company
DC	Direct Current
DEG.	Degree
δ	Vertical Tire Deflection for Pure Vertical Loading Conditions
Δ	Delta Differential
°F	Degree Fahrenheit
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FT	Feet
g	Acceleration of Gravity (32.2 ft/sec^2)
GR	Gross
Hz	Hertz (cycle per second)
HR	Hour
IAS	Indicated Air Speed
IN	Inches
k	Spring Rate
KTS	Knots, One Nautical Mile per Hour, or 1.15 Mile per Hour
LBS	Pounds
LMLG	Left Main Landing Gear
MAC	Mean Aerodynamic Chord
MAX	Maximum
MI	Miles
MIN	Minimum
MPH	Miles per Hour
N/A	Not Available
NASA	National Aeronautics and Space Administration
NO.	Number
#	Number
NTSB	National Transportation Safety Board

LIST OF ABBREVIATIONS

O.D.	Outside Diameter
OZ	Ounces
%	Percent
PLCS	Places
PSI	Pounds per Square Inch
PSIA	Pounds per Square Inch Absolute
PSIG	Pounds per Square Inch Gage
r_R	Rolling Radius
r_S	Static Radius
RAD	Radians
RF	Radio Frequency
RPM	Revolutions per Minute
RTO	Rejected Takeoff
SEC	Seconds
SEM	Statinary Electronic Module
T&RA	Tire and Rim Association
TEMP	Temperature
TO	Takeoff
TPI System	Tire Pressure Indicating System
TPMS	Tire Pressure Monitoring System
TYP	Typical
VDC	Volts, Direct Current
VS	Versus
W	Width of Tire
WT	Weight
W.U.	Wheel Unit

I. INTRODUCTION

Six prototype cockpit tire pressure indicating (TPI) systems have been flight test evaluated on two McDonnell Douglas DC-10's between October 1978 and January 1979. Three prime systems were thoroughly evaluated on one DC-10 during a 52 flight, two month program that included a broad range of operational conditions including hard landings, maximum performance braking during landings and rejected takeoffs, sharp taxi turns, and long cruise flights. The other three systems were less intensively evaluated with the results included in this report to help highlight TPI design criteria.

The impetus for the flight test evaluation of tire pressure indicating systems came from the initial study, "Feasibility and Cost-Effectiveness of Airborne Tire Pressure Indicating Systems," Report No. FAA RD 78-134,I. Throughout the study it was apparent that the exactness or thoroughness of the study of different system concepts was limited by available information on hardware that was not fully developed. Parts of the study were based on manufacturer's claims and predictions and were not backed up by actual laboratory or aircraft test data. Before a system could be selected for production,, some aircraft development testing was required. The results of these tests are reported here as Part II of the study.

The report discusses the selection of the participants for the test and the system design criteria that formed the basis for the selection emphasizing the system's ability to detect and prevent false warnings. Each system considered for test is briefly described including a system concept that appeared to have considerable promise but has never been reduced to practice. One concept not tested by Douglas (the wheel speed approach - concept N in Part I) is discussed in some detail because of its ease of installation and relative low cost. The wheel speed system was tested by an airline on a DC-9 airplane and the results are included in the Appendix.

Each concept tested is described in some detail including a discussion of installation requirements. All laboratory test and flight test data on the concept is presented and discussed. The report emphasizes the three primary systems tested - the transformer coupled analog system, the direct signal bearing coupled analog system, and the bogie strain/weight and balance relative tire load measuring system. Test data are presented including flight crew comments and a discussion of development problems encountered and their proposed resolution.

II. SELECTION OF TEST PARTICIPANTS

A. DESIGN CRITERIA USED FOR SELECTION

The system selection criteria was derived from the results of Part I of the Feasibility and Cost-Effectiveness of Tire Pressure Indicating System Report.

1. False Warnings - Freedom From

Per Part I "the main design criteria by which all systems are judged in this report, is their ability to operate 100% free from false warnings. In other words, a cockpit indicating system shall be able to always differentiate between an actual low pressure tire and a tire that merely appears to be low through a system fault." The reliability analysis and the tradeoff study in Part I of this report comments further on the ability of the systems to meet this criteria with additional comments on the primary systems tested included in the discussion of systems selected.

2. Passive Failure Detection

"The second design criteria, and only slightly less important, is that the TPI system should be capable of detecting its own passive failures that would cause it to fail to properly indicate a low tire. The estimated ability of each system to meet this criteria is also discussed in the Reliability section (in Part I).

"Although it may be argued that the high reliability of a particular design or the short exposure period on takeoff roll makes the probability of false or passive failures remote, still it is believed that approaching the design from the viewpoint of allowing no false warnings and undetected passive failures will ultimately produce a system that most closely meets this objective."

3. Development Status/Experience and Installation

The third selection criteria is self-explanatory. Hardware that would most closely represent a production installation was, of course, most favored. No manufacturer had commercial aircraft experience with their TPI system but some had built hardware for laboratory test and aircraft test. A key selection criteria was ease of installation of hardware at the wheel/aircraft interface.

4. Different Concepts

Systems most desired were those that presented unique or different concepts to the solution of the most difficult design problem, which is communicating tire pressure information from the inside of the rotating tire into the aircraft. Once a participant for a type of system was selected, similar systems, although perhaps nearly equally worthy of merit, were rejected.

5. Test Hardware Supplied at No Cost

All participants were requested to supply hardware at no cost to the Douglas Aircraft Company or the FAA. This requirement applied equally to all interested vendors and was a factor in one promising system not being tested.

B. SUMMARY OF SYSTEMS EVALUATED

Requests for proposal for participation in the flight test program were sent to twenty-three possible subcontractors. The request included a preliminary specification for a cockpit indicating system and requirements for participation in the test program. More than ten proposals were received; three of which were selected for the test program. A brief review of the systems that were not selected and the reasons they were not selected follows:

Approach/Concept	Evaluation
1. Differential Valve - Discrete (Concept I, Part I Report)	
Differential valve opens when tire pressure drops below predetermined level which ports remaining tire air pressure into tube that actuates bellows in wheel hub area. The bellows makes electrical contact across rotating air gap as a momentary high force slip ring.	Discrete pressure sensing systems were not favored because specific sensor failure modes cannot be differentiated from actual low tire pressure and passive failures - failures to indicate a low tire when it occurs, and general difficulty of aircraft checkout caused rejection of this concept (see criteria 1 and 2).

Approach/Concept	Evaluation
2. Discrete TPI System (Concept J, Part I Report)	
This system employs a wheel mounted pressure switch the state of which is detected across an air gap by a rotating coil passing by a stationary coil once every tire revolution.	This system was the best thought out and implemented system of its type with excellent electronic and pressure switch designs. Tests of a similar system by DAC on a DC-10 (reported herein) confirmed reservations on the viability of this approach.
3. Analog Tire Pressure via Slip-Rings (Concept G, Part I Report)	
The system proposed using a wheel axle positive contact signal coupler (slip ring) to carry the transducer signal into the aircraft.	Interested airlines and Douglas had prior unfavorable experience with slip-rings and installation in the wheel/hub environment was questioned. The manufacturer offered no supporting test or other data to satisfy the concerns about the slip-ring approach. Although direct connection to transducer has advantages, this particular approach was rejected (Design Criteria #3).
4. Wheel Speed Sensing (Concept N, Part I Report)	
Aircraft wheel speed taken from antiskid transducer outputs (already available on all study aircraft) is used to detect low tires by detecting small wheel speed differences of adjacent tires due to changes in rolling radius.	The wheel speed approach was favored for ease of installation and cost. A study (Appendix A discusses in detail) showed that differences in rolling radius due to different manufacturer's designs caused excessive speed differentials for normally inflated tires. (Design Criteria #1 and 2) As tire matching on an axle had been

Approach/Concept	Evaluation
	flatly rejected by a number of operators this approach did not appear to be a general solution. It may, however, be a satisfactory solution for operators that use one tire manufacturer, if the specific circuit design minimizes failure warnings. (See Appendix B for airline test results.)
5. Tire Air-Force Coupling (Not evaluated in Part I)	
This concept required bringing tire air into the wheel hub to actuate the bellows which would apply a force proportional to tire air pressure on a force sensing transducer.	Concepts requiring the bringing of tire air into the hub area was not favored due to increased tire leak exposure across the wheel/hub cap interface. Two other similar concepts were rejected for this reason (Concept F, Part I Report). (Design Criteria 1 and 3) Accuracy was also a question.
6. Induced Power RF Transmission	
This concept installs a small RF transmitter at the pressure transducer mounted on the wheel. The transmitter is energized by power delivered across two antennas separated by 1/2" air gap. The analog pressure is transmitted back across the same antenna coupling into the aircraft. System faults can be isolated by performing a calibration test cycle prior to displaying the low tire indication.	(No specific proposal has been received to date. The justification for this concept would be if the antennas can be so mounted as to eliminate the need for an electrical connector in the hub cap area.)

Approach/Concept	Evaluation
7. Passive Element Hi-Q Pressure Transducer	
Four different companies proposed variations of this concept. The resonant frequency of a passive element circuit on the wheel is varied as a function of pressure. The resonant frequency (frequency at which maximum power absorption occurs) is measured via RF antenna coupling from on-board computer.	This very promising concept was not tested since each company was unwilling or unable to supply hardware (criteria #5). Concept also has not been bench tested. It offers simplicity of wheel mounted hardware, ease of coupling, and meets all failure criteria. A new pressure transducer design would be required.

Selected Systems

The following systems were selected for participation in the test program:

Approach/Concept	Evaluation
1. Analog Pressure via Axle Transformer (Concept D, Part I Report)	
A pressure transducer mounted in the wheel is powered by electronic circuits packaged in the wheel hub which is energized by high frequency AC signal from transformer coupler mounted in hub. A signal, the frequency of which is proportional to tire pressure, is sent back across the transformer to on-board computer.	Concept had been fully developed in the lab and successfully tested on aircraft wheels with reasonable accuracy demonstrated. Wheel installation was straightforward although it did not eliminate the need for an electrical connector on the wheel. The system shows good potential to eliminate false warnings and has complete test capability.

Approach/Concept	Evaluation
2. a) Analog Pressure via Signal Bearing	
A pressure transducer mounted in the wheel is directly connected to an on-board computer via a signal carrying bearing mounted on the face of the antiskid wheel speed transducer in the hub cap.	This system was selected due to potential advantages in increased accuracy and reduced cost due to direct coupling of transducer. Due to the novelty of the coupling scheme, a second system was offered to be tested in parallel which offered an alternate coupling method that bypassed the hub cap electrical connector interface.
b) Analog Pressure via Inboard Wheel Couplers	
A pressure transducer mounted in the wheel is powered by electronic circuits mounted on the wheel which receives power and transmits encoded pressure information via inboard wheel mounted coupling rings.	
3. Percent Tire Load via Bogie/Axle Strain (Weight and Balance Approach) (Concept 0, Part I Report)	
This system uses newly designed variable reluctance strain measuring transducers lug-mounted on main gear and in-axle mounted on nose gear. Differential strain is measured to determine percent load on each tire. Weight and balance is also available from this system without additional hardware.	This system offers a cost-effective alternative to low tire detection while providing weight and balance data. Provides indication after push back of a significant problem developing on taxi or takeoff roll. Used in conjunction with wheel mounted gauges it offers a complete system. The most difficult design task is accurately detecting problem while aircraft is rolling on uneven pavement.

The following system was not part of the official test program but was tested on the same aircraft primarily for a different purpose (weight and balance). As tire pressure indication was included the results are briefly reported herein for completeness.

Approach/Concept	Evaluation
4. Low Tire Detection via Axle Tilt (Weight and Balance System) Low tire pressure is determined by sensing the inclination of the beam or axle which is due to non-uniform loading on the tires. The system sensors are closed loop servo inclinometers, mounted on the bogie beam for main gear and inside the axle for the nose gear.	
5. Go-No-Go Discrete Pressure Low tire pressure is sensed by a pressure switch in wheel. Pressure switch shorts secondary of air gap transformer mounted on inboard side of wheel. Primary coil of transformer mounted on stationary part of brake housing can detect open or short in secondary coil once per wheel revolution and produce an appropriate alarm. (Similar to Concept J, Part I of this report and approach 2 that was rejected.)	The supplier of this hardware built a four wheel system directly adapted to the DC-10 and supplied it to DAC well before the present test program was to take place. This system was tested on DC-10 ship 254 on a non-interference basis.

III. FLIGHT SUMMARY - CONDITIONS COVERED

The tire pressure indicating systems were monitored during normal operational conditions, including numerous takeoff and landing cycles, moderate to hard braking, sharp taxi turns, and during cruise flights with altitudes and outside air temperatures noted. The DC-10 test aircraft accumulated 52 flights with tire pressure indicating systems on-board.

Due to the effects of hot brakes after numerous takeoff and landing cycles, tire pressures go up considerably. Without excessive braking, tire pressures increase between 15 to 20 psi during normal taxi for approximately two miles before takeoff. After repeated takeoffs and landings, tire pressure increased from 170 to 230 psi with normal braking during landing. The TPI systems, with some exceptions, performed satisfactorily during many takeoffs and landings.

On the analog pressure system the original pressure differential allowed between wheels on a common axle had been selected to be 10%. It was found, however, that during the numerous takeoff and landing cycles condition, the 10% differential must be either increased or inhibited in-flight to avoid false annunciator warning as the outboard main gear tires dropped in pressure more rapidly than the inboards. This may be due to the way the landing gear retracts, the lower wheel being nearer the skin, gets colder than the adjacent wheel above the warm brake. As a result, the pressure differential for alarm was changed to 14.2%. No false warnings appeared thereafter.

From the hard braking and sharp taxi turn test, it was found that tire load was transferred from one wheel to the other as the center of gravity shifted. During hard braking, a slight pressure increase with brakes applied of approximately +2 psi was noted. During turning, a side load effect was noticed as a slight pressure transfer to the mating tire occurred of approximately +2 psi. The braking and turning effects, however, did not affect the tire pressure readings or alarms as the pressure readings immediately normalized after the maneuvers.

The systems performed satisfactorily while cold soaking above 30,000 feet altitude for many hours. The lowest outside air temperaturre measured was -20°C at an altitude of 35,000 feet.

Periodically, actual tire pressures were recorded by the ground crew and compared with TPI system pressure. Some tire pressures were recorded for both pre-flight and post-flight to check the TPI system accuracy. Occasionally, selected tires were deflated to check system warning thresholds. For the percent tire load system which operates on the basis of weight and balance techniques, a tire bleeding test was done to check warning thresholds and transducer output behavior.

IV. EVALUATION OF THE SELECTED SYSTEMS

(1) ANALOG PRESSURE VIA AXLE TRANSFORMER

A. SYSTEM DESCRIPTION

This system displays actual tire pressure of any selected wheel continuously (see Concept D, Part I). The system was installed on wheels 1 and 2 of the test aircraft. The pressure can be monitored whether the aircraft is stationary, taxiing, taking off, landing, or airborne throughout the entire flight. With the wheel mounted transducer, the tire pressure data is picked up and transmitted through an inductive coupling (transformer) to the processing and display unit. This system is shown diagrammatically in Figure 1. The system's self-test feature prevents false warnings of low tire pressure. If any tire falls below a programmable minimum threshold, then an annunciator light is illuminated automatically and the low tire identified on the display. The flight crew can, if desired, rotate the selector switch to any wheel number and display the actual tire pressure.

All failure modes are detected while the system is operating. With the exception of the lamp test (which is done manually), all other faults are displayed automatically each time an individual tire pressure is checked. The system is designed to perform an automatic self-test before displaying a low tire indication. If a system fault is detected to be causing the low tire indication, the low tire light is suppressed.

The entire operation of the system is accomplished from the display panel in the cockpit. Only readjustment of the threshold pressures requires access to the TPI computer. Binary switches will be provided inside the computer cover in production. For the test system, one switch was provided. With rotary wheel selector switch on AUTO (see Figure 2 which shows the cockpit display panel as installed for test), the TPI system is automatically and continuously interrogating all the tire pressures on the aircraft. Interrogation time for a 12 wheel aircraft will be between 3 and 4 seconds.

For the normal system operation, interrogation will continue automatically as long as power is on the aircraft and the selector switch is on AUTO. If there are no low tires, the display will be blank.

If one low tire is below threshold (for flight test, this was set at 135 ± 5 psi) or approximately 15% below the adjacent tire or 15% below average of all tires in same threshold group, then the warning light on the cockpit annunciator panel will be turned on. The cockpit display will then display the low tire number.

ANALOG PRESSURE SYSTEMS

(Systems 1 & 2)

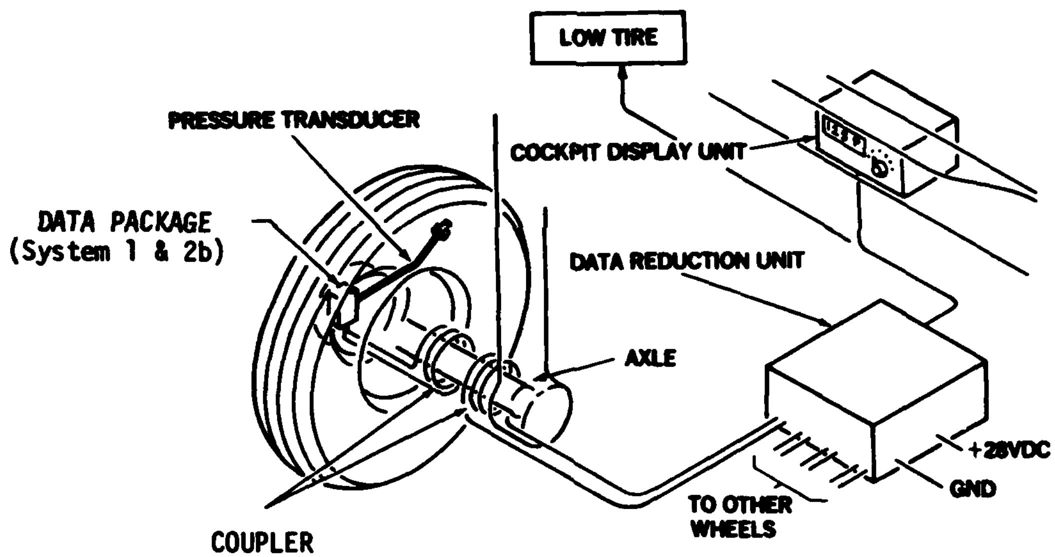


FIGURE 1

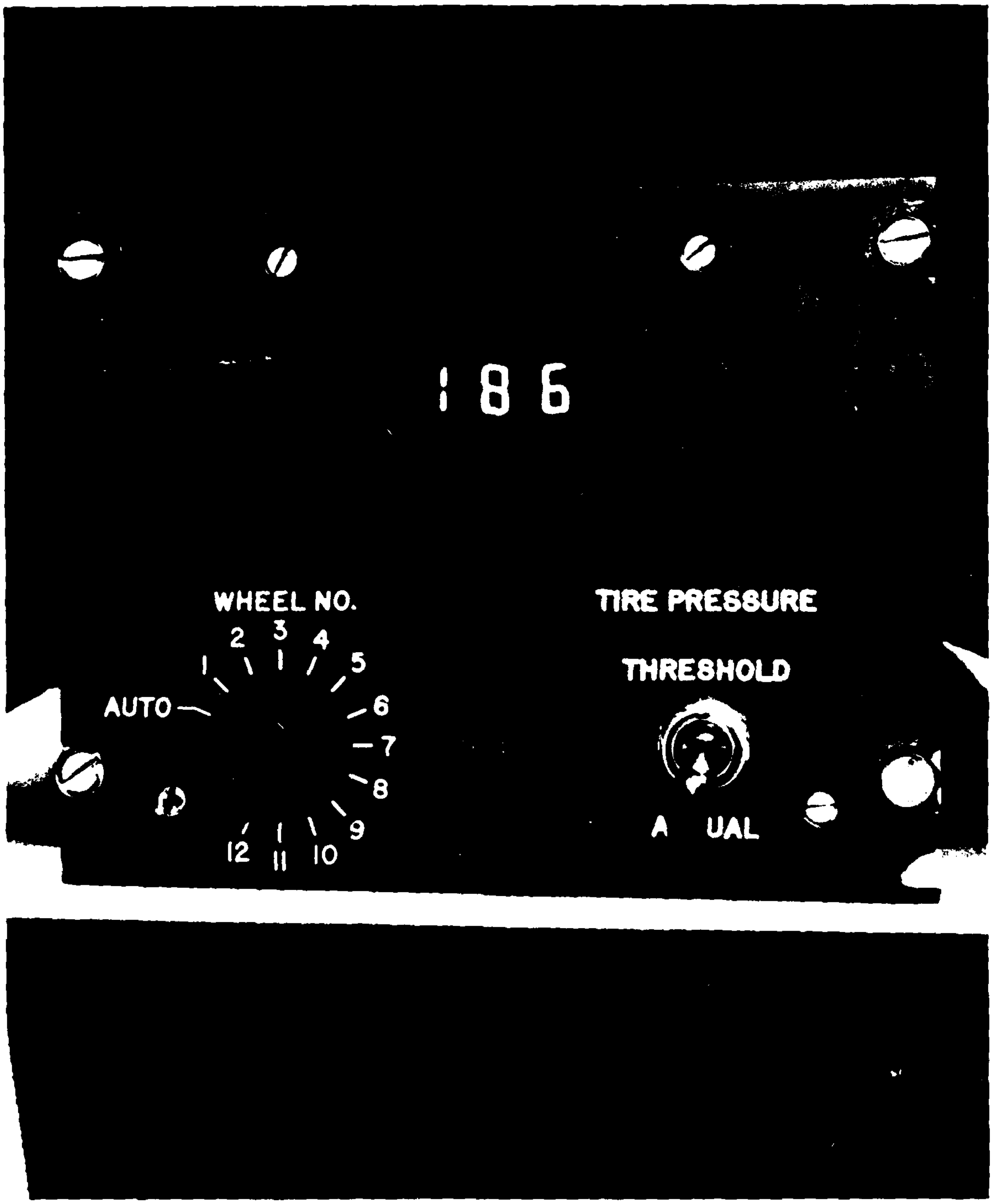


FIGURE 2. TEST INSTALLATION OF COCKPIT DISPLAY FOR SYSTEM NO. 1
(ANALOG PRESSURE)

If multiple low tires are detected, the cockpit "low tire" light will illuminate and the display will sequence the display of the wheel numbers at the interrogation time intervals (every 3 to 4 seconds a different wheel number will be displayed and the sequence will be repeated indefinitely).

At any time that there is power on the aircraft, the flight crew can check any or all tires for their actual and threshold pressures. This is accomplished by rotating the selector switch to the wheel number of interest. The actual tire pressure in that wheel will be displayed (see Figure 2 for wheel #1 pressure display). If the spring-loaded toggle switch is held up to the THRESHOLD position, then the threshold pressure for that tire will be displayed (in this case 135 psi).

While tire checks are being made, automatic interrogation of the TPI system continues and if a low tire is detected, the cockpit "low tire" light will be illuminated. Then to determine the identification of the low tire, one need only return the rotary selector switch to the AUTO position.

For the system fault detection, if the system is free of all faults when the test button is depressed, three 8's will be displayed while the button is held in. The "low tire" light on the overhead panel is also illuminated while the TEST button is held in. When the button is released, a GO will be displayed for a few seconds and then the display will go blank. The sytem is then back in normal automatic interrogation mode of operation.

If there are any faults in the TPI system they can be identified by pressing the TEST button. Regardless of the fault or faults, when the button is held in, the digital readout is checked (8's displayed) along with the overhead annunciator panel light. When the TEST button is released and a fault in one wheel exists, an F followed by the wheel number is displayed continuously. Normal interrogation continues for possible additional faults or a low tire condition. The low tire warning light will illuminate even though the system is in the TEST mode but to identify the low tire number the TEST button must be pressed again putting the display back into the normal operating mode.

For multiple wheel faults, an F in front of the wheel numbers will be displayed at interrogation intevals (3-4 seconds) and continues to repeat the wheel numbers in sequence until the TEST button is depressed a second time. Again, this puts the display back into the normal operating mode.

For a TPI system fault, an FF will appear on the display continuously if a fault occurs which is central to all wheels, such as an oscillator failure. In the unlikely event of power supply failures such that no display is possible, a circuit has been added that illuminates the TEST button bulb. This bulb should always be on when aircraft power is on. A bulb test can be effected if the bulb is out by noting if an expected display appears.

Interrogation for low tire detection continues but may be inhibited due to the nature of the system fault. Depressing the TEST button a second time will put the system and display back to the normal operating mode.

This display configuration was developed for the flight test program. The system can be made to work with a broad variety of displays from a "low tire" light only to a full display similar to that used by system #2 described next.

B. LABORATORY TEST RESULTS

Laboratory tests for the components were performed by the system subcontractor. Three pressure transducers were individually checked and calibrated against the manufacturer's test records. The results correlated very closely. Then each of the three transducers were calibrated with each of the three wheel electronic assemblies at room temperature for a total of nine combinations. Table I shows the results. It indicates a maximum of 2% error in the working area of from 100 to 200 psi.

TABLE I

TRANSDUCER VS WHEEL ELECTRONICS @ ROOM TEMPERATURE

THEORETICAL PRESSURE AT ROOM TEMP. (psi)	TRANSDUCER	1	2	3	1	2	3	1	2	3
	WHEEL ELECT.	2	2	2	4	4	4	5	5	5
0		-	-	-	-	-	-	-	-	-
50		50	50	50	49	50	50	49	49	48
100		101	100	100	101	100	100	100	100	100
150		151	150	150	154	150	150	152	152	149
200		206	202	202	205	202	203	203	203	206
250		257	253	250	257	251	253	257	257	259
300		309	-	-	306	-	-	-	-	-

TABLE II
LABORATORY TEST RESULTS ON COMBINATION OF
TRANSDUCER AND WHEEL ELECTRONICS

Transducer #2
Wheel Electronic #2

THEORETICAL PRESSURE (psi)	PSI READINGS — Temperature effect results minor difference in pressure reading compared to theo. pressure					
	50°C	100°C	150°C	0°C	-40°C	-45°C
50	50	52	-	47	47	47
100	100	101	96	99	99	99
150	150	152	148	150	150	151
200	200	205	199	203	202	202
250	245	257	251	257	255	255
300	-	309	303	-	-	-

Transducer #3
Wheel Electronic #2

THEORETICAL PRESSURE (psi)	PSI READINGS				
	50°C	125°C	0°C	-40°C	-54°C
50	50	58	45	40	38
100	100	107	95	92	91
150	150	159	146	143	143
200	202	212	195	194	195
250	253	263	-	249	249
300	306	-	-	300	300

TABLE II
(continued)

Transducer #1
Wheel Electronic #2

THEORETICAL PRESSURE (psi)	PSI READINGS			
	97°C	0°C	-40°C	-54°C
50	56	44	42	43
100	104	96	95	96
150	154	146	146	148
200	205	198	198	200
250	255	249	251	255
300	306	298	303	306

Transducer #1
Wheel Electronic #5

THEORETICAL PRESSURE (psi)	PSI READINGS	
	125°C	0°C
50	42	42
100	95	96
150	145	149
200	199	200
250	-	250
300	-	300

Table II shows the test results of temperature tests run on combinations of transducers and wheel electronics. All three transducers were run with two of the three wheel electronics units. The third wheel electronics unit was tested through the temperature range but not formally calibrated. During the test, one of the transducer and wheel electronics combinations was inadvertently exposed to -75°C for about 5 minutes. It operated producing significant errors but then recovered completely.

All three wheel electronics were rechecked through the pressure range after potting with Sylgard and after final assembly into the hub caps and onto the antiskid transducer. All test results were consistent with the calibration data.

With the wheel system installed on the wheel and tire assembly in the laboratory, the tire was inflated to 180 psi. Pressures were checked over a three day period with no evidence of any leakage. Then the entire wheel and tire installation was rotated up to 120 rpm. The system functioned normally.

According to the data, the transducer behaved very well in the range of room temperature to 100°C. Lower and higher temperatures do affect the accuracy of the pressure readings; a difference with the actual theoretical pressure of 12 psi and 13 psi respectively. In addition, the pressure range giving the highest accuracy is below 200 psi. Above that, a pressure error of 9 psi was measured. Thus besides the temperature effects, the transducer will respond optimumly only at certain pressures (this level is, of course, selected to be most accurate at the normal tire inflation pressure).

Also, with different calibration factors for each transducer and wheel electronics unit, it would be advantageous to match transducers and wheel electronics to minimize errors. However, the transducer and wheel electronics units should be interchangeable. Thus, no matter which combination of units is used the same readings should be obtained at a particular temperature. This could be achieved by putting in a calibration factor each time a wheel electronics unit or transducer is changed. For instance, if one transducer reads 5 psi higher, a calibration factor could be included such that the error is nulled. If very high accuracy is demanded, calibration may be required. Otherwise ease of interchangeability is desired without recalibration each time a component (or wheel) is changed.

<u>Lab Test Data Error/Accuracy Summary</u>

Per DAC tire pressure indicating systems preliminary Specification A112065, Paragraph 3.1.5 under System Design Criteria states, "The calibration or sensor error shall not exceed ± 3 psig at 200 psig when operating with the temperature range of +40°F (+4.4°C) to +120°F (+48.9°C). The scale error that can be met for the -40°F (-40°C) to +40°F (+4.4°C) and +120°F (+48.9°C) to 300°F (148.9°C) ranges shall be specified by the subcontractor. These tolerances shall be met without regard to mounting position."

The transducer performed most accurately in the temperature range from 50°C to 100°C. The transducers and wheel electronics combination were within ± 4 psi at 150 psi and ± 6 psi at 200 psi over a reasonable temperature range. At low temperature, the pressure tends to read lower than the theoretical pressure. At higher temperature it follows that higher pressure is recorded. Normally brake temperature operates at ambient temperature to about 100°C. Only during heavy braking and numerous takeoff and landing cycles will high temperature be experienced at the brakes. Therefore, for normal temperatures reasonable accuracy can be obtained.

During the flight test program outside air temperatures were periodically recorded during the flight. Temperatures of -25°C were encountered at high altitude. In addition, hot brakes during rejected takeoff could result in a temperature as high as +200°C. Within this full range (-25°C to +200°C), larger errors are expected, however, no damage or calibration shift was noted in the transducer or wheel electronics. Effect of lower temperatures will be evaluated in planned service tests.

More accuracy can be achieved by means of matching the transducer and the wheel electronics. This could minimize the error introduced. Table II gives a good example of the matching technique. The combination of transducer #1 and wheel electronics #2 appears to be less worthwhile as errors are larger. However, if we matched wheel electronics #2 with transducer #2 or #3, the errors introduced are minimized. This matching technique has advantages, but a preflight lab test must be performed in order to match components and it may be required to change both the wheel electronics and transducer at the same time despite the fact that only the transducer or the wheel electronics unit has failed. Although matching is a good way to minimize errors it is not recommended due to maintenance and logistics difficulties that the technique imposes.

C. INSTALLATION/MAINTENANCE

The installation involves the TPI computer, TPI cockit display panel, transducer and adapter assembly, and hub cap coupler and wheel electronics. The TPI computer and the TPI cockpit display panel can be installed without difficulty. To install the transducer and adapter assembly, wheels have to be removed and tires have to be deflated. The entire assembly is installed in the pressure release plug port. Although this is a simple operation in a tire shop, it may be a cumbersome task to change the transducer on the aircraft. This requires stocking extra wheels with the entire TPI asssembly already installed. Thus to replace a defective transducer the entire wheel will most likely be changed. During flight test a failed transducer was replaced with the tire on the aircraft without fully deflating the tire with relative ease. This, however, bypasses the normal overnight tire leak check and may not be an acceptable airline maintenance procedure. Thus a one manhour tire change may be required when transducers fail.

The installation of the hub cap coupling and wheel electronics was very straight-forward. The antiskid transducer adapter in the axle required a wire clearance hole so that the wires for the tire pressure coupler could come through the axle. With the modified antiskid transducer drive shaft (see Figure 3) on the end of the axle, a locating tool is used to locate the fixed coil concentric to the antiskid shaft.

Transducer and Adapter Assembly Installation procedure outline

1. Remove wheels to be retrofitted for TPI from aircraft.

2. Deflate tires to be retrofitted.

3. Remove pressure release plug and the two adjacent wheel nuts.

4. Install clamp plate assembly and reinstall two adjacent wheel nuts, finger tight. (Insure reinstallation of nut washers.)

5. Install pressure release plug into transducer and adapter assembly, and install entire assembly into pressure release port, finger tight.

6. Assemble cushioned clamp and Flexloc nut to clamp plate and torque to 25 in-lbs.

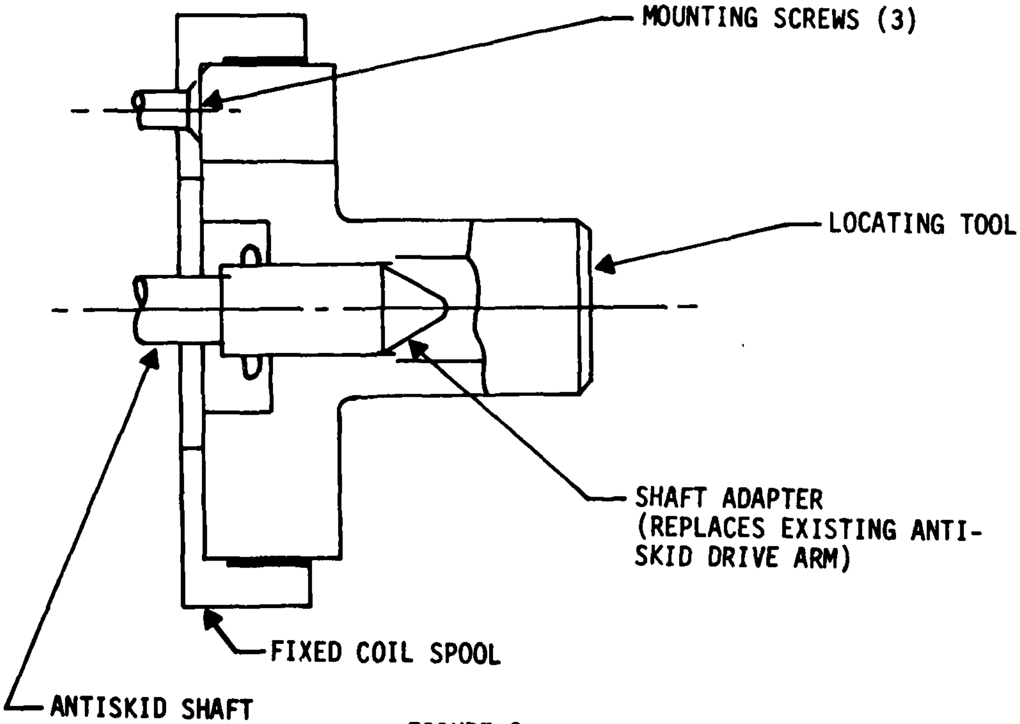


FIGURE 3

MODIFIED ANTISKID TRANSDUCER DRIVE SHAFT

7. Torque wheel nuts (2) to 135 ft-lbs.

8. Torque pressure release plug and banjo bolt adapter to 200 in-lbs.

<u>Hub Cap Coupling and Wheel Electronics Installation Procedure</u>

1. Remove antiskid transducer.

2. Add wire clearance hole to DAC transducer adapter.

3. Splice twisted pair wires to fixed coil assembly using environmental splice.

4. Install modified antiskid transducer and fixed coil assembly with three (3) flat head (100°) screws, finger tight.

5. Using locating tool to locate fixed coil concentric to the antiskid shaft and torque the three (3) mounting screws to 25 in-lbs, and remove locating tool (see Figure 3).

6. Mount hub cap and wheel electronics assembly to wheel and orient cable. Connect connector to transducer and tighten by hand only. (Do NOT use a tool.)

7. Tighten hub cap clamp per DAC specifications.

8. Safety wire banjo bolt to adapter and pressure release plug to adapter.

9. Safety wire connector to coupling nut and back shell.

NOTE: Typical hub cap coupling and wheel electronics installation is shown in Figure 4.

Installation of the system was quite straight-forward and took a minimum amount of time. Transformer coupler and hub cap electronics installation took only about 1/2 manhour per wheel with most of the time being consumed by locating and drilling the wire access hole in the antiskid wheel speed transducer mounting adapter.

Mounting of the transducer and adapter on the wheels similarly was straight-forward. Only one minor problem was encountered when the holes in the stainless steel adapter plate were not large enough for the larger wheel bolts which placed a slight side load on the adapter fitting causing an air leak at the wheel mounting. This was readily corrected and no further leaks were encountered. Mounting of each transducer adapter assembly, including tire deflation and reinflation took about 1/2 manhour.

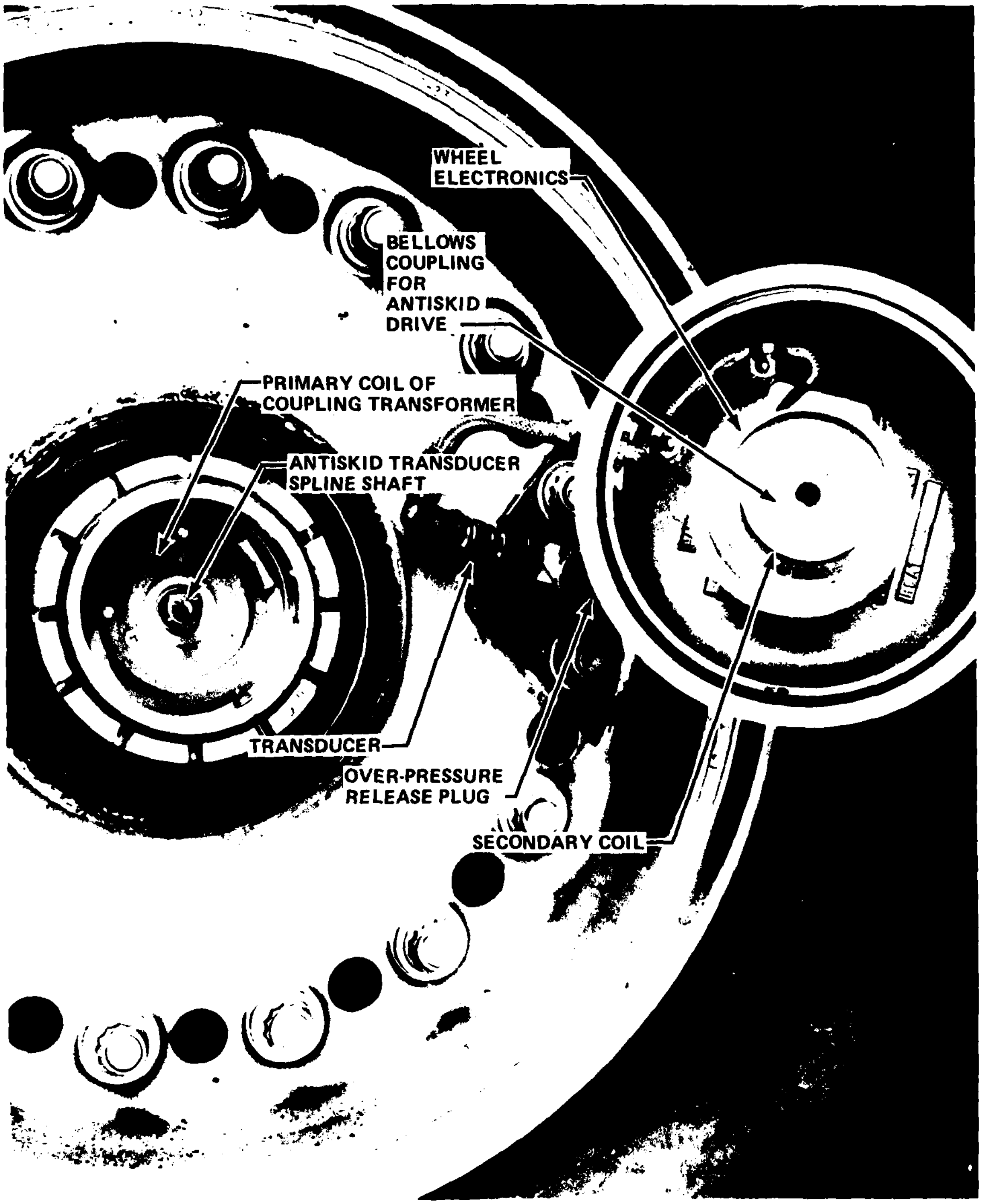


FIGURE 4. TYPICAL INSTALLATION FOR HUBCAP COUPLING AND WHEEL ELECTRONICS

D. FLIGHT TEST RESULTS

The system performed very well throughout the flight test except for several minor problems. The first of these was a power transient problem caused during bus switching in the aircraft. When power would momentarily drop the program would lock up and the system would fail to operate when power was restored unless circuit breakers were opened and reset. This problem was corrected in software and no further difficulty was encountered with bus switching.

Another minor problem that developed early was the "low tire" light coming on during cruise. As can be seen in Figure 5 and other figures, the tire pressures tended to diverge during cruise with tire #1 dropping in pressure more rapidly. As the initial tire pressure differential used was 10% this threshold was increased to 14.2% and no further problems were encountered. This did, however, bring to light the need to take into account such things as the differential pressure caused when a tire is replaced after landing when all the other tires might be at an elevated pressure and the new tire installed at nominal pressure. This can also be easily taken care of in system software programming.

During system installation actual tire pressure was compared to cockpit displayed pressure using a $\pm$ 1/2 psi accuracy gauge. All readings were found to be within 3.5%. Another minor problem was noted, however, that remained throughout the test program. The last digit of the pressure, particularly on wheel #2, would vary sometimes as much as 3 to 4 psi. This should be corrected in the production system.

The system threshold was checked and rechecked on initial system installation and worked correctly. All fault display codes were also checked with various faults introduced in the system and all worked properly.

During actual flight operations the system responded normally wihin $\pm$ 5 psi of the actual tire pressure meaasured. Several occasions, however, it was within $\pm$ 10 psi. The transducers provided good results during takeoff, climb, cruise, and landing. The typical transducer output characteristics is shown in Figure 5 with the system in the auto mode. The tire pressure reading occasionally oscillated within $\pm$ 2 psi. All data were hand-recorded by the flight engineer.

The system was able to pick out pressure loss due to fuse plug release during a high energy rejected takeoff demonstration. It picked up the flat tire before the ground maintenance did. Initial pressure loss was quite slow but increased in rate at about 205 psi. The system performs satisfactorily for every flight condition, even heavy braking. Typical tire pressure response is shown in the graphs in Figures 6 and 7 during all operational conditions and landing cycles and hot and cold cycles.

One case of failure occurs as shown in the Flight No. 19 and 20 plot. The profile is shown in Figure 8 showing a calibration shift in one transducer (see problem discussion section).

FIGURE 5

TYPICAL TIRE PRESSURE PROFILE

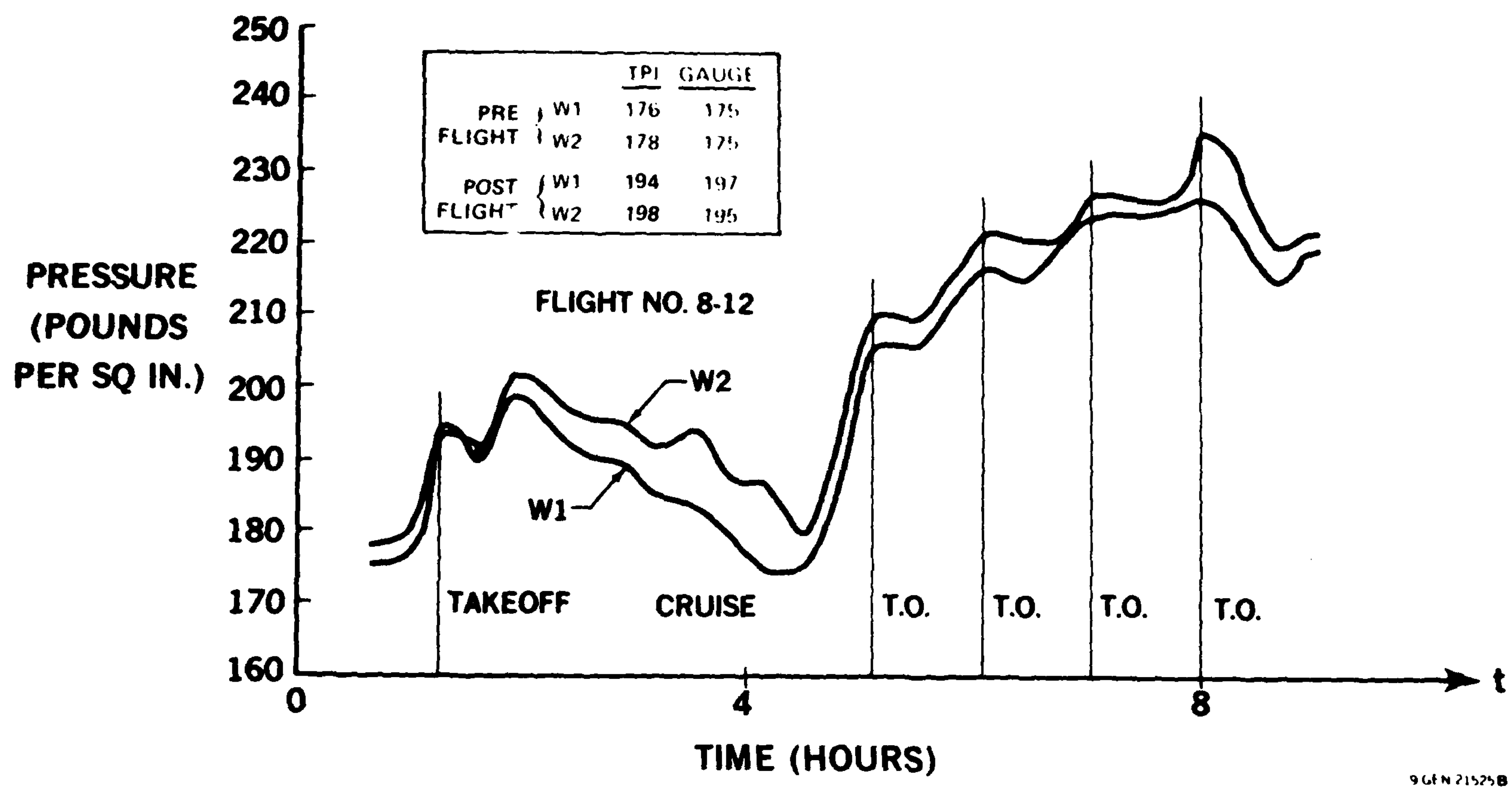


FIGURE 6

TYPICAL TIRE PRESSURE PROFILE

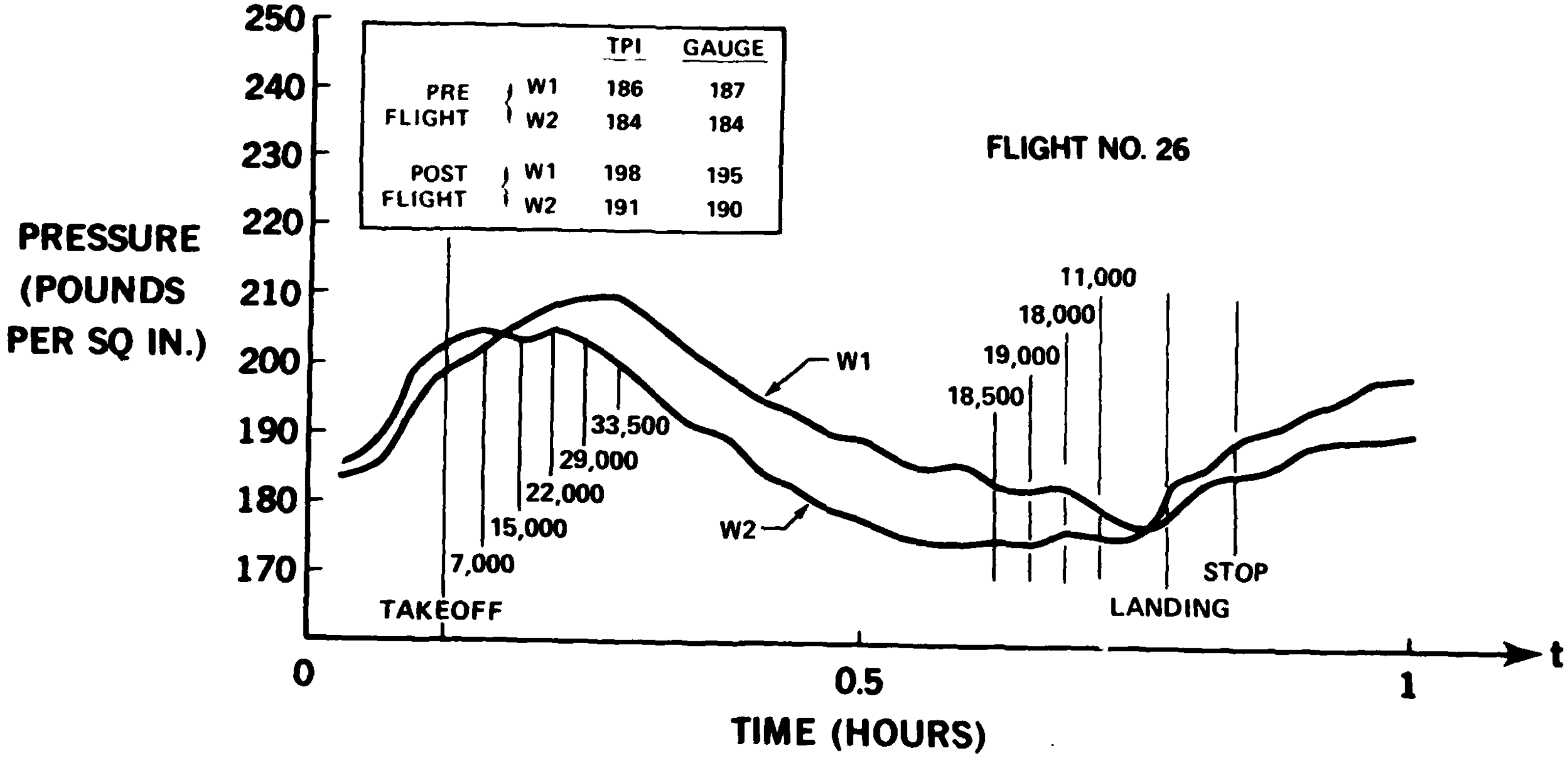


FIGURE 7

TYPICAL TIRE PRESSURE PROFILE

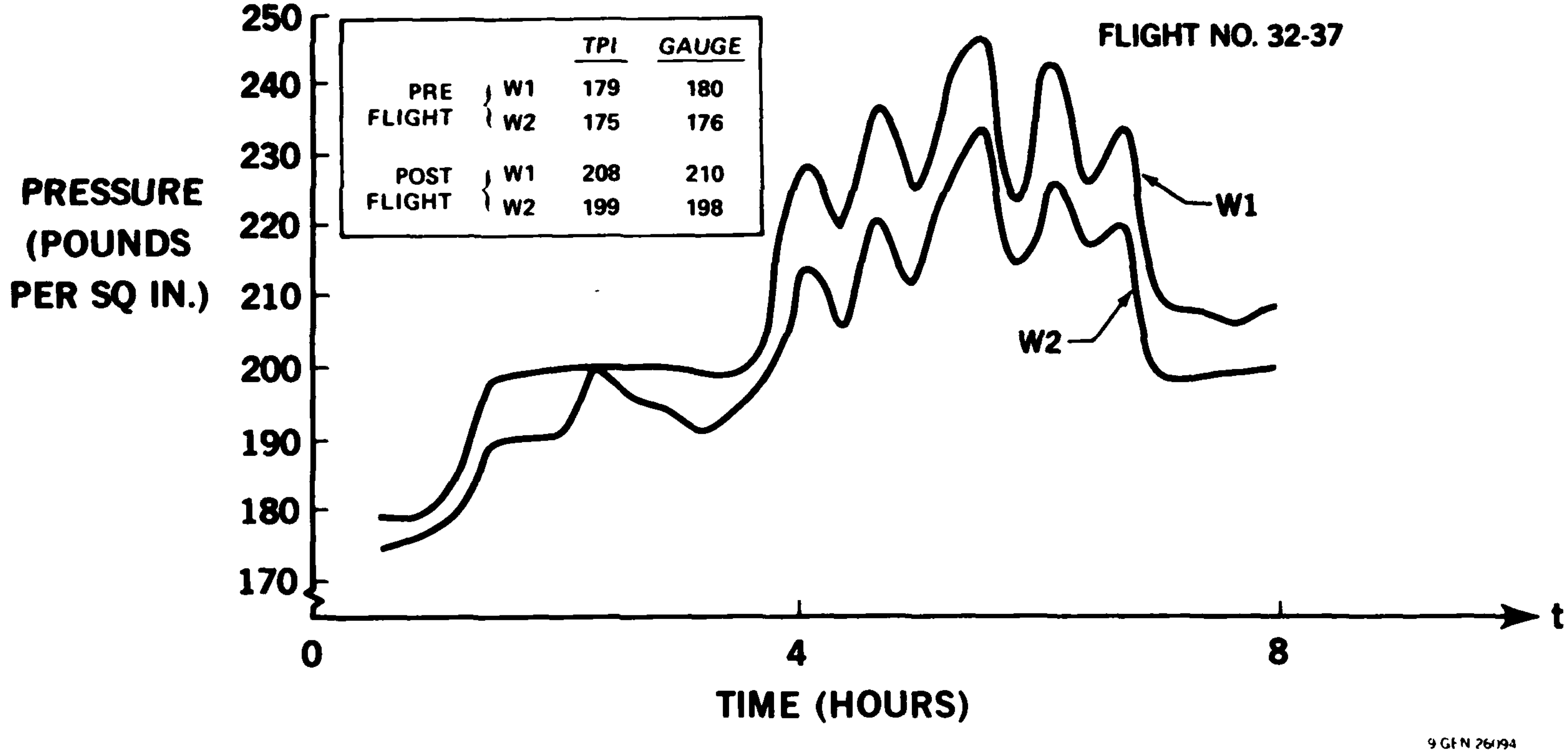
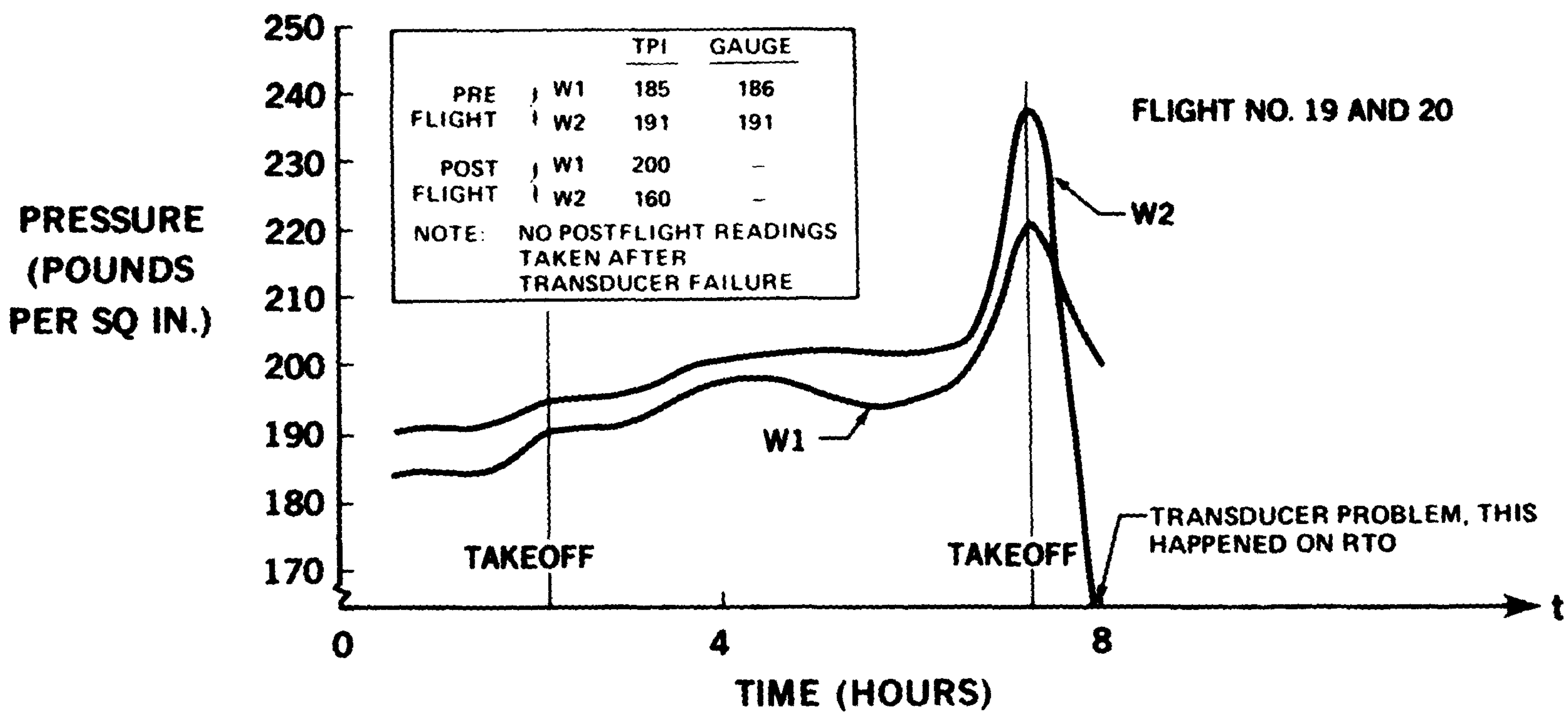


FIGURE 8

TYPICAL TIRE PRESSURE PROFILE



E. PROBLEMS ENCOUNTERED/RESOLUTIONS

During installation one fault signal occurred. It was later found that the wheel electronics module wasn't working due to an open wire. Another wheel electronic hub cap assembly was installed. After that the system worked satisfactorily during the entire flight program. With the extra hardware added to the wheel, wheel balancing was required. Weights of 30 in-oz and 50 in-oz were added to wheel #1 and wheel #2 respectively. As wheel balance is typically checked at each tire change in-service this would not require additional maintenance time.

At the beginning of the flight test program, a power transient problem was encountered as mentioned earlier in the report. The need to pull out the circuit breaker to restore the computer memory was later eliminated by a software change.

On flight 20, tire pressure on wheel #2 dropped from 230 psi to 160 psi after the moderate energy rejected takeoff. The problem was later found by the transducer manufacturer to be a faulty transducer due to off-center soldering on one of the gauge pads in the transducer. The lead solder extended over the edge of the gauge pad and allowed a leakage path to develop with time causing an unbalanced bridge. This is shown in Figure 9. Improvements in quality inspection have been provided by the transducer manufacturer. Corrective action is vital as this is the only failure mode found in the system that would give a false warning of low tire pressure.

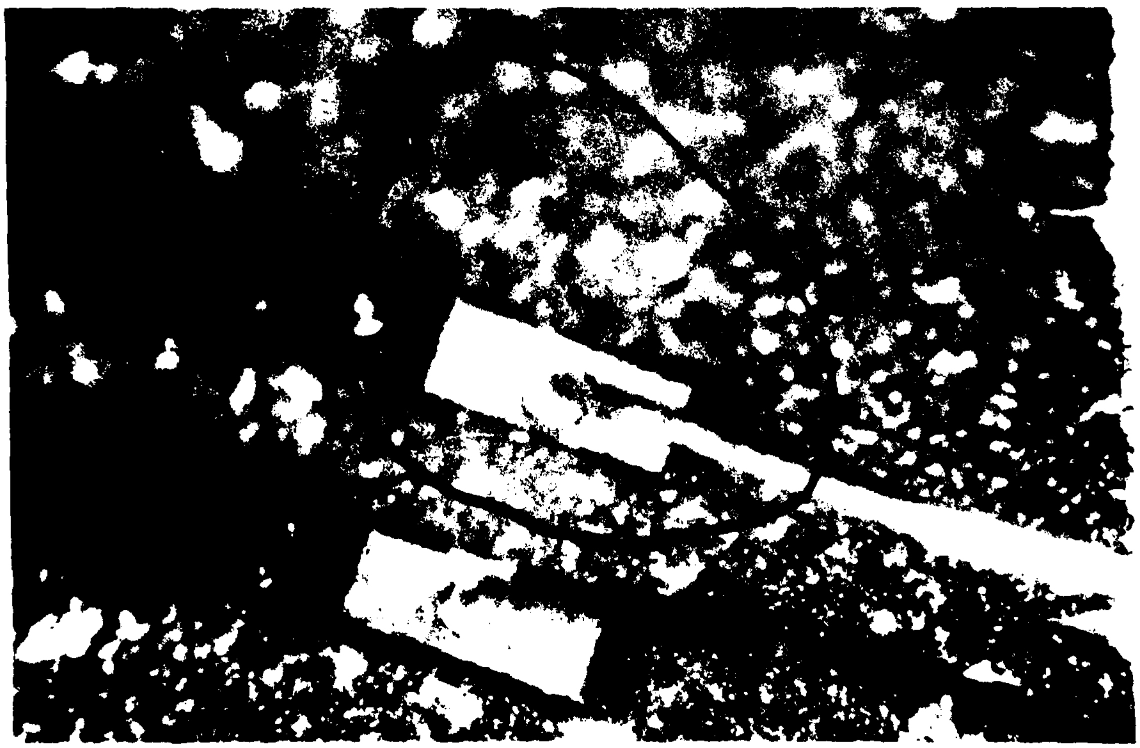


FIGURE 9. FAILED SOLDER PAD UNIT

As mentioned earlier, the 10% tire differential threshold had to be increased to 14.2% to prevent low tire indications during cruise.

During the heavy (75% of max energy) rejected takeoff, the TPI hardware performed satisfactorily. No damage occurred on the system and the system did provide immediate warning of the first slow leak in a tire due to fuse plug melt.

F. PILOT COMMENTS

Many of the pilot and flight engineer comments involved undesired aspects of the prototype display such as wheel selector knob size and spacing between wheel numbers that will be corrected in production with different display types. The flight engineer also wanted an automatic system fault annunciation as the prototype system only provides a fault display when the self-test button is pushed.

Other pilot/flight engineer comments were:

1. The "low tire" light should be suppressed if the tire pressure is above 200 psi (nominal tire pressure is 180 to 190 psi).

2. Cycling time interval (tire pressure update rate) is between 3 and 4 seconds. It was suggested that this be made 1 second max.

3. The "low tire" light should be connected to the Master Caution Annunciator system.

4. Last pressure digit oscillation of ± 2 psi was not desirable.

(2) ANALOG PRESSURE (two methods)

One supplier offered two different approaches to coupling information from the rotating wheel into the aircraft. These concepts were tested on two wheels each and displayed on a common cockpit monitor.

a. Signal bearing coupling system.

A. SYSTEM DESCRIPTION

A wheel mounted variable resistance type pressure transducer is driven by a constant current sent to the wheel through a ball bearing assembly acting as a slip ring and the voltage drop across the combined bearing and transducer resistance is measured as an indication of pressure. The ball bearing assembly is mounted on the face of the antiskid wheel speed transducer (see picture of installation in Figure 10) and is driven by the wheel speed transducer drive shaft. A wire is brought from the pressure transducer to the hub cap area and is terminated in a small connector on the drive arm of the wheel speed transducer. The wheel speed transducer drive shaft completes the electrical path to the inner face of the ball bearing assembly and a wire attached to the outer face runs through the axle and up to the control box which provides the constant current source and other signal processing.

A precision constant current source was used to induce a reference voltage proportional to transducer position. An absolute pressure transducer was used so that a non-zero reading was obtained even for a flat tire. A valid reading within the approved resistance band must be maintained. If the pressure excursions exceed window limits again both the wheel BIT (see cockpit display panel, Figure 11) lamp and the master fail lamp would light. The wheel BIT lamp would go out if the wheel again entered valid limits, but the master fail light can be cleared only by turn-on reset.

Description of the display panel (Figure 11). The display panel consists of the following.

1. Pressure readout gauge. It indicates the lowest tire presssure at all times. Initially the display panel was calibrated in psig, thus reading approximately 15 psi higher than the normal tire pressure reading. This was to aid in fault detection since zero tire pressure would be 15 psi. This was later changed to eliminate confusion with higher than normal readings.

2. Pushbutton for each individual wheel. Find out the tire pressure of a particular tire by pushing the corresponding button. The lamp face is split into three output flags in which each one is under independent software control.

   (a) Low. The low pressure output flag is turned on if the pressure from that wheel is less than the threshold level established by the front panel "digit-switches" for that gear category. There are three gear categories - nose, main, and center with a separate set of threshold adjustments for each category.

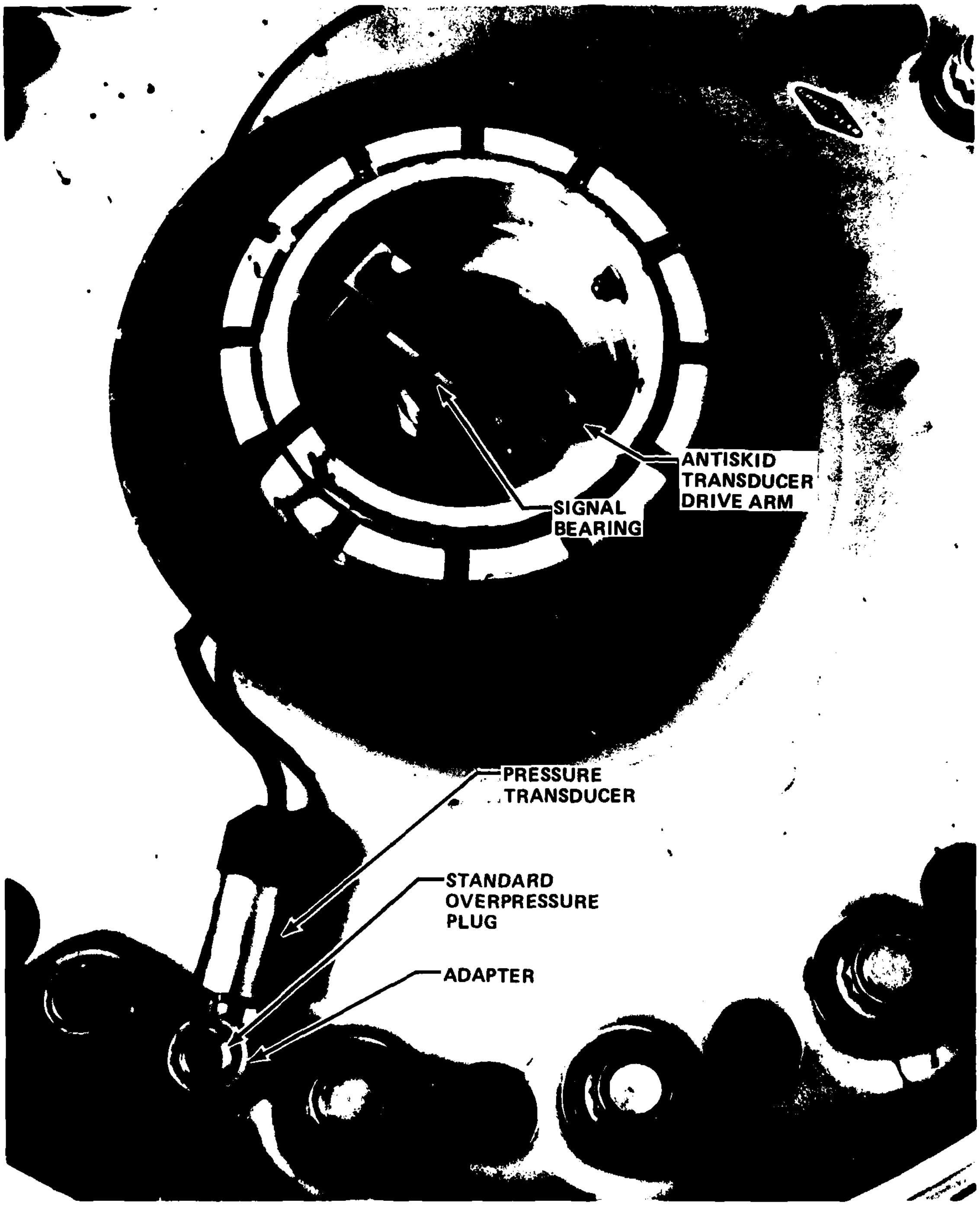


FIGURE 10. ANALOG PRESSURE,SYSTEM 2 A,SIGNAL BEARING MOUNTING

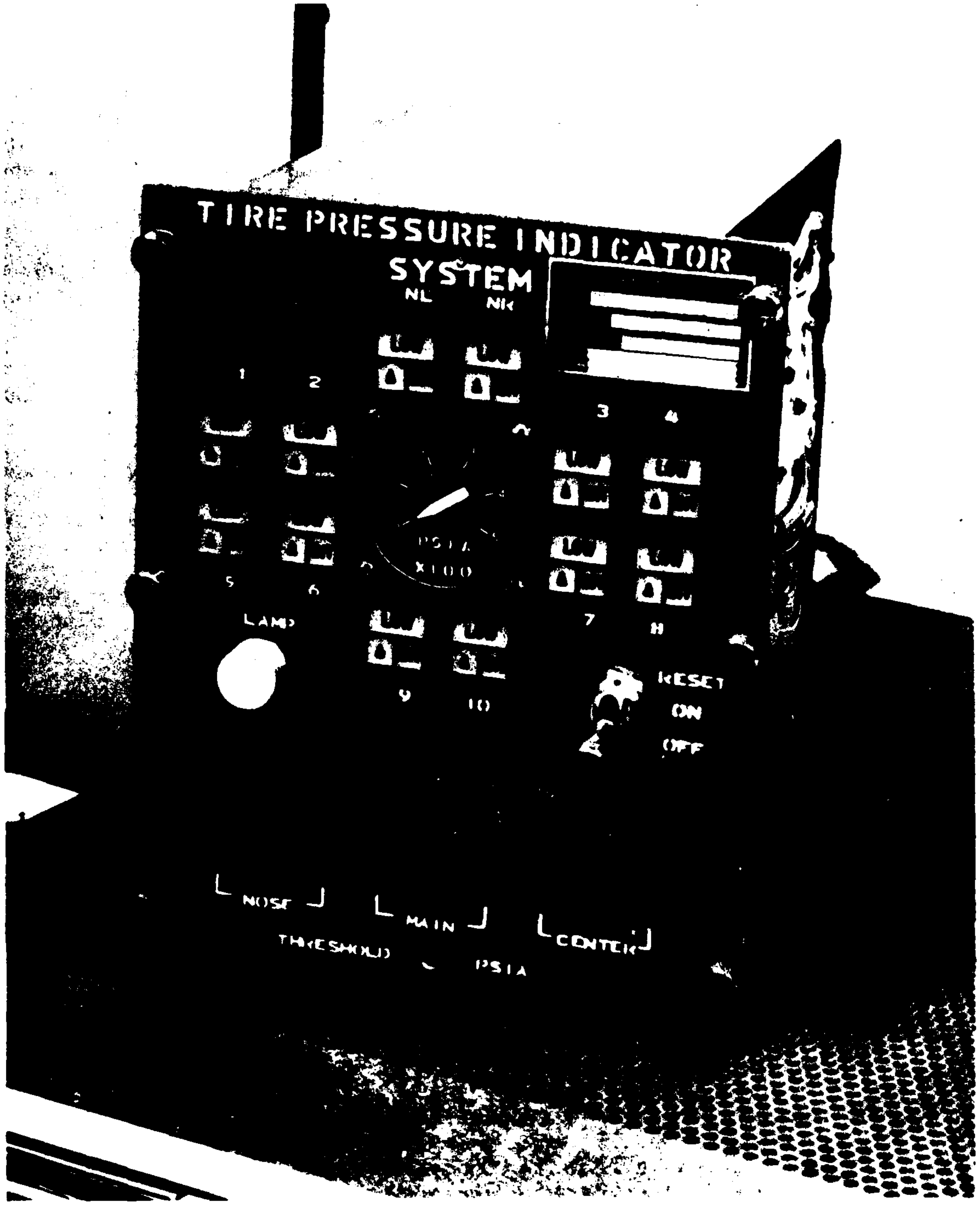


FIGURE 11. ANALOG PRESSURE COCKPIT DISPLAY, SYSTEM 2

(b) "Δ". The delta pressure flag is an indication of a lack of symmetry between wheels of the same category. The differential level is set at 35 psi. If the particular tire is 35 psi or more higher than the mating tire, then the "Δ" light comes on.

(c) "BIT". The BIT or built-in-test flag is an indication that there is a system channel fault. The sensor data is out of specification and the data is considered to be unreliable. If the built-in-test determined that a sensor had malfunctioned, a pressure indication of 500 psi is placed in the output register for that wheel.

3. Threshold switches. The purpose of the threshold switches is to permit the operator to adjust the trip level for the display flags. A full range of zero to 999 is provided for each of the three categories. The wheel categories are main gear, nose gear, and center gear. These switches would not be located on the panel for a production system but alteration of warning thesholds would be provided for.

4. Lamp test. The lamp test switch enables all of the lamps on the display. This is a software lamp test in that the request switch is an input request to the control processing unit (CPU) which then uses existing drivers to turn the light on.

5. Reset switch. The reset switch cleared possible computer hangups and reset the alarm flags used to indicate failures.

B. LABORATORY TEST RESULT

The signal bearing system was set up in the laboratory for dynamometer testing. Two wheels were instrumented, one not rotating and the other rotating on the dynamometer. The results are shown in Table III. The pilot's monitor light will come on when any one of the three lights are on. First, there is the low pressure light which indicates tire pressure falls below the established threshold level, second is the delta light which indicates a pressure differential of 35 psig drop in pressure, and third, there is the BIT (Built-in-Test) light which indicates a circuit failure.

As a certain required threshold was set, the rotating tire was deflated gradually until either the low light came on, or the delta light came on, depending on whichever occurred first. For instance, Table III showed that run #3 has the low light on first since the required threshold was set at 149 psig. However, in run #5 with the required threshold set at 133 psig, the delta light came on first due to a pressure differential of 35 psig. Then the low light followed. The TPI monitor readout was 8-10 psig lower compared to the required threshold throughout all the runs. This error represents an excessive resistance of approximately 30 ohms in the transducer-signal bearing loop.

RUN	BRAKE CONDITION	LANDING SPEED (MPH)	UNLAND SPEED (MPH)	STARTING TIRE PRESSURE (PSIG)	REQUIRED THRESHOLD (PSIG)	* T.P.I. MONITOR READING (PSIG)	** ACTUAL PRESSURE BY GAUGE (PSIG)	** ACTUAL PRESSURE BY OSCILLOGRAPH (PSIG)
						LOW LIGHT	DELTA LIGHT	DELTA LIGHT
1	DRY	214.20	193/COAST	176	165±2	-	-	-
2	DRY	25.00	0	175	165±2	160	-	-
3	DRY	200.00	190/COAST	173	149±2	142	-	-
4	DRY	200.00	195/COAST	173	141±2	136	136	138
5	DRY	200.00	195/COAST	173	133±2	127	135	137
6	DRY	200.00	195/COAST	174	125±2	116	135	137
7	DRY	200.00	195/COAST	174	117±2	109	136	138
8	DRY	200.00	195/COAST	175	109±2	101	136	137
9	DRY	200.00	195/COAST	174	100±2	90	136	138
10	DRY	212.06	129/COAST	174	165±2	160	-	-
						MONITOR LIGHT WAS ON		

* LOW LIGHT ON ONLY WHEN THE PRESSURE WENT BELOW THE REQUIRED THRESHOLD PRESSURE

** DELTA LIGHT CAME ON WHEN A PRESSURE DIFFERENTIAL WAS 35 PSIG BETWEEN THE FULLY INFLATED STATIC TIRE AND THE DEFLATED ROTATING TIRE

TABLE III

DYNAMOMETER TEST, RESULTS FOR SIGNAL BEARING SYSTEM

C. INSTALLATION

On installation of the signal bearing system, a modified hub cap and an improved antiskid transducer drive coupler was installed. New electrical connectors were spliced to the pressure transducer leads to accommodate the new hub caps.

During installation, the pressure transducer standoff fitting in the pressure relief plug port had to be lockwired at its base to prevent the turning of the prssure transducer. This could be done only if the wheel is disassembled into halves. Thus the installation involves the breakdown of the wheel which is not desirable for production installations.

A modified wheel speed (antiskid) transducer with ball bearing slip rings was used which merely replaces the existing antiskid transducer. The electrical connection between the transducer and the signal bearing was unacceptable for production and was damaged in flight test (see Figures 12 and 13). Installation times were quite comparable with the transformer coupled system discussed first.

D. FLIGHT TEST RESULTS

This system utilized a ball bearing slip ring to carry electrical current across the rotating joint to power the pressure transducer, in which resistance varied proportionally with pressure. Voltage drop across the transducer was the tire pressure indicator. It was installed on wheels 3 and 4 of the tested DC-10 aircraft. Modified wobulator type antiskid transducer drive hub caps were installed. New electrical connectors were spliced to the pressure transducer leads to accommodate the new hub caps.

System characteristics were observed and evaluated during the test program. First, the system has a built-in-test (BIT) which, when a failure is detected, lights a BIT light for the failed wheel and drives the pressure indication to 500 psi for that wheel. This was observed on several occasions due to open circuits encountered in the signal bearing couplers. Also, the pressure transducer is an absolute pressure type so the cockpit display indicated absolute pressure (psia). This is 14.7 psi greater than the gauge pressure (psig). The tires were inflated to 190 psig which was 205 psia.

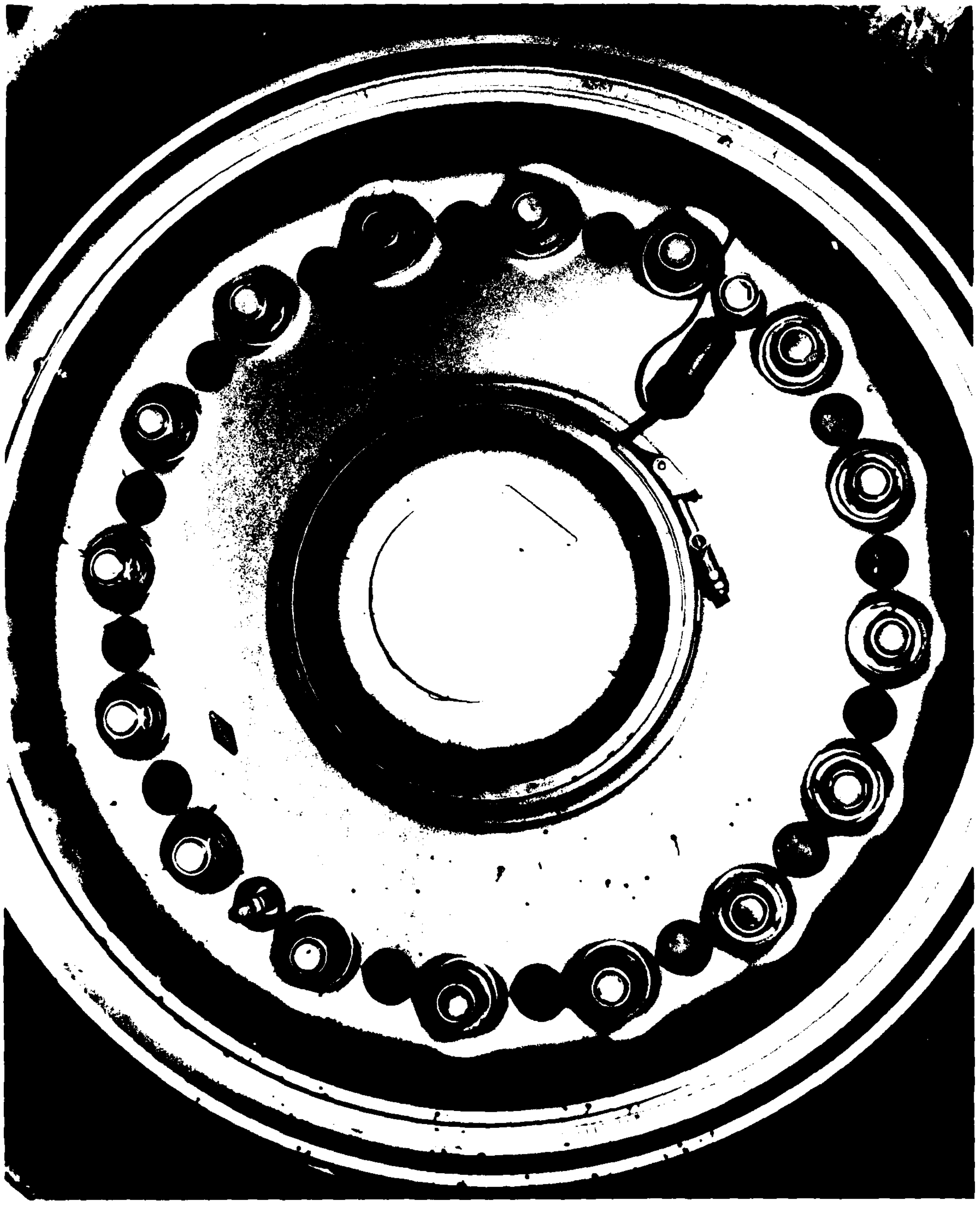


FIGURE 12. OUTER VIEW OF SIGNAL BEARING SYSTEM

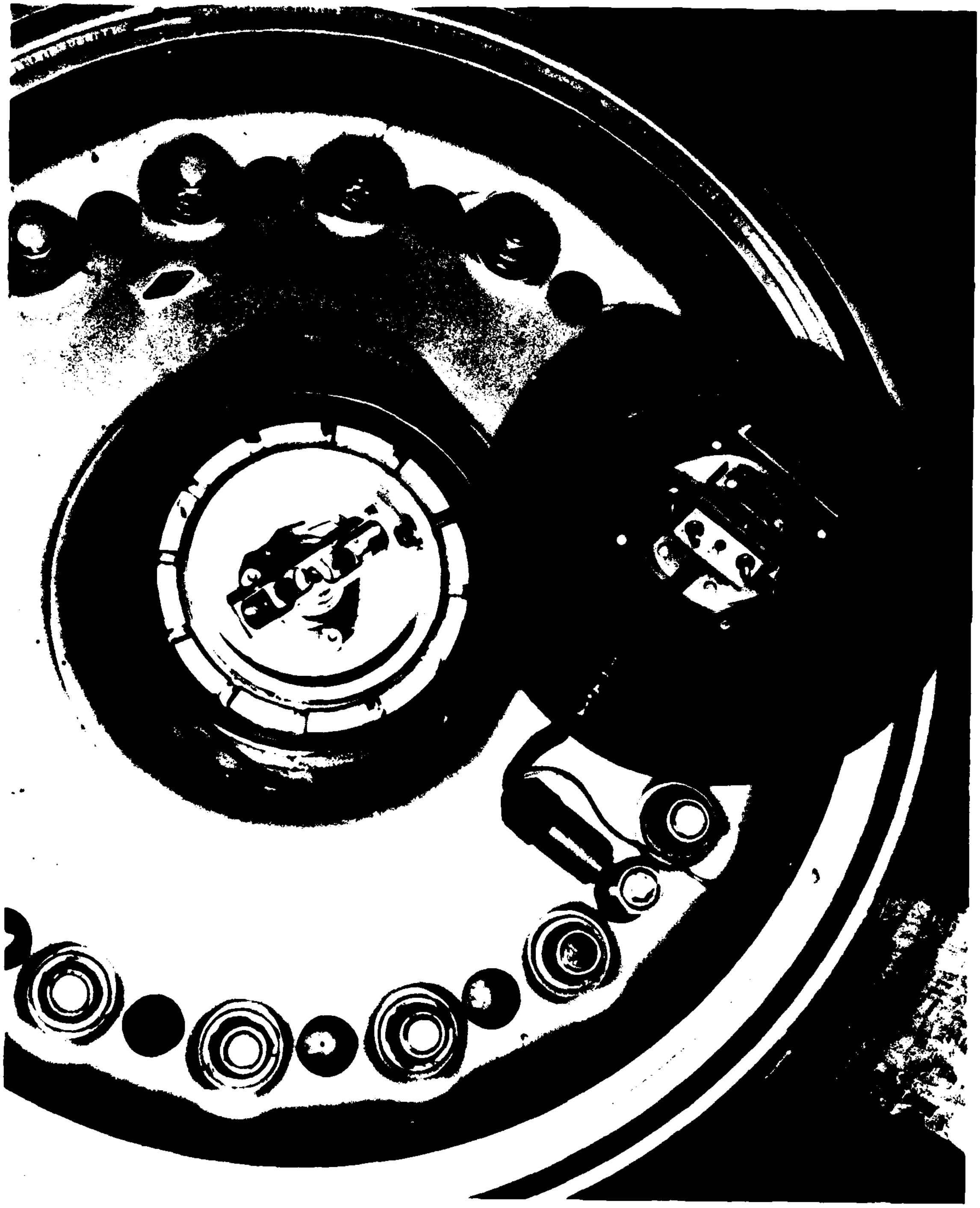


FIGURE 13. INNER VIEW OF SIGNAL BEARING SYSTEM

Initially the system showed indications of producing pressure indications which varied directly with aircraft rolling velocity. To overcome this speed sensitivity which appeared to be due to development of a lubricant film between the bearing balls/rollers and faces, the ball bearing slip ring unit was redesigned. (It is interesting to note that the problem did not occur during dynamometer testing.) Whereas the original ball bearing unit contained one ball bearing signal path with the return through the wheel main bearings, the redesigned unit has two bearings for signal and return. The bearings were lubricated with conductive grease, but tests showed it was still speed sensitive. Subsequent cleaning of the bearings and impregnation with a small quantity of dry powdered graphite resulted in a non-speed sensitive unit with low electrical resistance.

Wheel #3 malfunctioned early in the task program. The indicator read 500 psig indicating an open circuit. The modified wheel speed transducer with ball bearing slip rings was removed and replaced with a standard wheel speed transducer. The ball bearing unit was then disassembled, and wire attached to outer bushing was found to be loose. The bushing was replaced, unit reassembled, and the repaired unit replaced on the aircraft. The unit again had been removed and replaced with a standard wheel speed transducer when an antiskid preflight wheel speed transducer spinup indicated a chattering antiskid valve.

The No. 4 wheel unit had been found to have high resistance (about 100 ohms) through bearings and to have an intermittent open circuit. The wire was resoldered to the outer bushing and the bearings relubricated with dry graphite. The #4 wheel coupler was later mated with the #3 wheel pressure transducer and worked satisfactorily throughout the remainder of the test program. Just prior to the high energy RTO, however, it was found that the cockpit indicator was reading 2 psig. The hub cap was removed and it was found that the pressure transducer wire was pinched between the hub cap and wheel which shorted the wire to the wheel (ground). The pinched point on wire was wrapped with tape and hub cap reinstalled. The unit then functioned satisfactorily during the rejected takeoff.

The wheel #4 system, prior to being installed on wheel #3, gave consistent readings that were 10 to 15 psi higher than actual tire pressure. This was not fully resolved but the #4 bearing assembly worked satisfactorily with the #3 wheel transducer.

During the high energy rejected takeoff demonstration, the system was able to pick out pressure loss due to fuse plug release. It picked up the flat tire before the ground maintenance did. Initially, the pressure loss was quite slow and the display was intermittent. The rate of pressure loss increased at about 200 psi.

E. PROBLEMS ENCOUNTERED/RESOLUTIONS

The signal bearing system was installed without any particular problem. During flight test, it was found that the pressure indications varied directly with aircraft rolling velocity, see Table IV. The system was then modified by adding conductive dry lubricant. After several flights, one wheel indicated failure. It read 500 psig which indicated an open circuit. The wire attached to outer bushing was found to be loose. With wire resoldered to outer bushing, the reading indicated 2 psig. This time the pressure transducer wire was found being pinched between the hub cap and wheel which shorted the wire to the wheel (ground). Pinched point on wire was wrapped with tape. One particular wheel had a 10-15 psi higher reading in the cockpit monitor than the actual tire pressure.

For the system, it can be made a reliable, simple system with improvements in the detail design of the bearing mounting, lubrication and electrical connections. The sealing of bearings keep lubricant in and contaminants out. Lubrication will include investigation of conductive lubricants, conductive coatings, and electroplating. Improved electrical connections to withstand handling and flexing. Improved material for bearing housing for higher strength and better platability. In addition, needs to simplify display lights and switching and redesign the transducers.

In production-wise, it appears possible and logical, since the pressure transducer produces a variable resistance, to combine the functions of the tire pressure monitor with those of the brake temperature monitor in the same cockpit display.

TABLE IV

AIRCRAFT SPEED VS. PRESSURE INDICATIONS

AIRCRAFT SPEED (MPH)	WHEEL #3 PRESSURE (PSIA)	WHEEL #4 PRESSURE (PSIA)
4	230	230
6	230	230
7	260	260
17	270	270
20	280	280
52	300	400
After RTO, Airborn	240 (Brake at 110°C)	250 (Brake at 140°C)

The signal bearing system did not prove to be satisfactory during the flight test program. Although the initial problem of tire pressures varying with wheel speed was largely resolved with the impregnation of the bearing with dry graphite, this solution was later shown by laboratory tests to be inadequate for long rolling life. In the laboratory the dry conductive lubricant eventually migrated away from the rolling balls degrading the characteristics of the bearing. Further, despite the partial resolution of the speed sensitivity problem the system continued to be plagued by malfunctions and intermittents such that usable data was only obtained during the last several flights of the test aircraft on one wheel.

The system manufacturer continued intensive development after the completion of the test program and has developed a direct contact coupling system that, based on laboratory tests, appears to resolve all the problems encountered during flight test. This must, however, be proven through further aircraft service evaluation.

b. Analog Pressure via Inboard Wheel Couplers

A. SYSTEM DESCRIPTION

1. This is a system based on the use of two externally mounted magnetic coupling rings for transfer of pressure data from the rotating wheel to the stationary hub (see picture of installation in Figure 14). Conventional schemes were then used for transmittal to the processor and display. The rings, approximately two feet in diameter, consisted of many turns of copper wire potted into a supporting metal form. One ring was mounted on the wheel and the other was mounted on the stationary brake housing so that the rings faced each other with a small air gap between them. Power was transmitted to a small electronic package on the wheel through the ring coupling and pressure data was transmitted from the wheel back through the rings to a processor box. A pressure transducer mounted on the wheel provided a variable resistance output which was monitored by the wheel electronics package. This wheel electronics package was designed so that the output frequency is directly proportional to the tire pressure of the wheel.

   The system operating band was set up to provide a preset window of valid readings. Operation of the wheel unit at frequencies for zero pressure and high pressure were within an approved band. Operation at frequencies outside the approved band were unacceptable as valid data and caused the BIT lamp (see System 2 cockpit display, Figure 11) of that particular wheel and the master fail lamp to light. If normal operation returned, the BIT lamp on the wheel went out, but the master fail light stayed on indicating a malfunction had occurred. The master

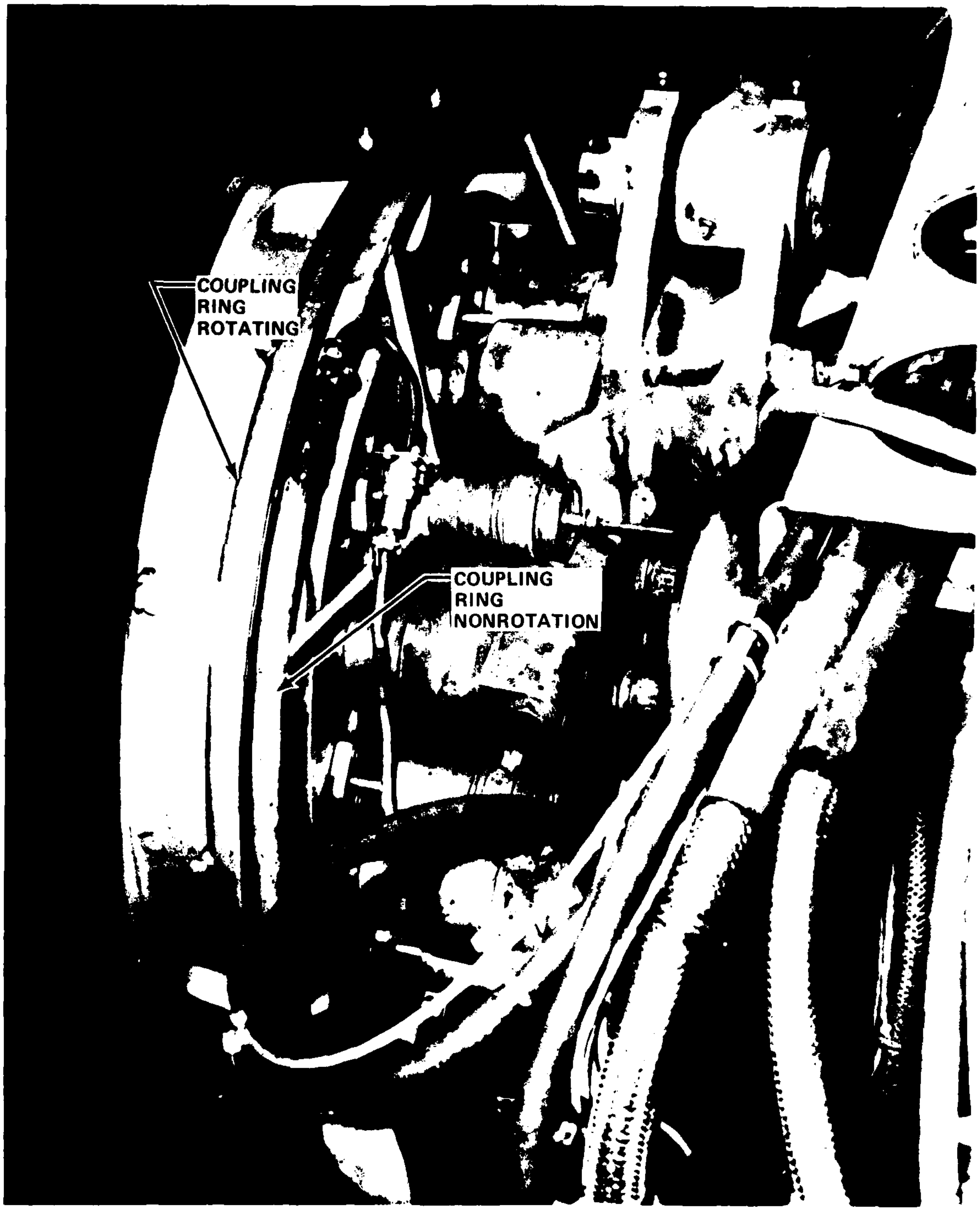


FIGURE 14. ANALOG PRESSURE,SYSTEM 2B,COUPLING RING MOUNTING

fail light can be cleared by the "reset" switch. If the computer senses a BIT fail on a wheel it recognizes the data is incorrect. If an operator request is made by pushing the wheel display button on a BIT failed wheel, the computer will put 500 psi on the analog meter. This represents the fault condition when valid data was not available.

B. LABORATORY TEST RESULTS

Several dynamometer test runs were performed under different conditions as shown in Table V. One tire was set at a starting pressure with readings taken statically (wheel not turning). This tire was used primarily for tire pressure comparison with the deflated rotating tire. The pilot's monitor light will come on when any one of the three lights are on. First, there is the low pressure light which indicates tire pressure falls below the established threshold level, second is the delta light which indicates a pressure differential of 35 psig drop in pressure, and third, there is the BIT (built-in-test) light which indicates a circuit failure.

As a certain required threshold was set, the rotating tire was deflated gradually until either the low light came on, or the delta light came on, depending on whichever occurred first. For instance, Table V showed that run #1 has the low light on first since the required threshold was set at 165 psig. However, in run #4 with the required threshold set at 133 psig. the delta light came on first due to a pressure differential of 35 psig. Then the low light followed. The TPI monitor readout was 8-10 psig lower compared to the required threshold throughout all the runs. This is probably a conversion error and appeared to have greater error at lower (110 psig and less) pressures.

C. INSTALLLATION

The inductive coils (hoola hoops) were installed on wheels 5 and 6 (left rear outboard and inboard). When adjusting the coils on wheel 5, it was found that the wheel mounted coil had a wide spot on its flange that made it impossible to adjust the coils to a nominal 1/8 inch clearance. When that system failed to operate, the coils were readjusted to the minimum clearance practicable. Rotating the wheel by hand then showed the system to be operating except over a small angle of rotation. No further attempt was made to adjust the coils on wheel 5.

The coils on wheel 6 were adjusted to the nominal 1/8 inch clearance and operated through full wheel rotation. However, after the first flight, the wheel showed failed (BIT light on) so the coils were readjusted to the minimum practicable clearance before the second flight.

RUN	BRAKE CONDITION	LANDING SPEED (MPH)	UNLAND SPEED (MPH)	STARTING TIRE PRESSURE (PSIG)	REQUIRED THRESHOLD (PSIG)	* T.P.I. MONITOR READING (PSIG)	** ACTUAL PRESSURE BY GAUGE (PSIG)	*** ACTUAL PRESSURE BY OSCILLOGRAPH (PSIG)
						LOW LIGHT	DELTA LIGHT	DELTA LIGHT
1	DRY	25.00	0	175	165±2	165	-	-
2	DRY	200.00	190/COAST	175	149±2	142	-	-
3	DRY	200.00	195/COAST	173	141±2	132	135	136
4	DRY	200.00	195/COAST	173	133±2	126	135	137
5	DRY	200.00	195/COAST	175	125±2	115	135	137
6	DRY	200.00	195/COAST	174	117±2	108	134	135
7	DRY	200.00	195/COAST	174	109±2	97	136	138
8	DRY	200.00	195/COAST	177	100±2	85	132	134
9	*	218.48	127/COAST	174	157±2	165	-	-
						MONITOR LIGHT WAS ON		

* WATER WHILE WHEEL WAS ROTATING

** LOW LIGHT ON ONLY WHEN THE PRESSURE WENT BELOW THE REQUIRED THRESHOLD PRESSURE

*** DELTA LIGHT CAME ON WHEN A PRESSURE DIFFERENTIAL WAS 35 PSIG BETWEEN THE FULLY INFLATED STATIC TIRE AND THE DEFLATED ROTATING TIRE.

TABLE V

DYNAMOMETER TEST, RESULTS FOR ANALOG PRESSURE VIA INBOARD WHEEL COUPLERS SYSTEM

D. FLIGHT TEST RESULTS

This system utilized inductive coupling across two large coils, one mounted on the inboard face of the wheel and the other on the adjoining face of the brake housing. The power to and the signal from the wheel mounted electronics were transmitted inductively through these coils.

The number 5 wheel system was inoperable through practically all of both flights in which they were tested. Subsequent inspection of the inductive coils revealed that during the flight test they had rubbed together to the extent that the coil encapsulant was worn through and the wires broken. The number 6 wheel installation read high (offset) and was somewhat erratic.

It was concluded that the large coil inductively coupled system, due to the necessity of maintaining a very small gap between the rotating and stationary coils, was impractical. In addition, large rings around the wheels looked vulnerable. They could be damaged from blown tire debris, by mechanics climbing on the wheels or by ice and snow compacting in the wheel during winter operation. when the coil gap was reduced due to differential ring expansion from brake heating causing rubbing of the coils and their eventual destruction, flight test evaluation was discontinued.

As a result of the testing, it was concluded that the large coil inductively coupled system, due to the necessity of maintaining a very small gap between the rotating and stationary coils, was impractical. In addition, the vulnerability of the system proved that it was not a practical tire presure system. Although impractical for the main gear installation this approach may be viable for the nose wheel where many small rings can be used on the inboard side of the nose wheel around the axle.

Summary of System Flight Crew Comments

Again, many of the flight crew comments were on prototype features of the test hardware which would be corrected in the production component. A summary of those comments are as follows:

1. Box is too big and complicated. It doesn't need to have threshold setting capability in the cockpit (this would be on front of remote computer for production.) It should be set by maintenance.

2. Digital readout is better than gauge readout. Scaling for the gauge reading is too large.

3. Flight crew preferred a combination display with both the brake temperature monitor and tire pressure indication by using one switch to select function.

4. Delta function could combine with low light.

5. Too much information given by the lights which creates more confusion.

6. Large rings around wheels #5 and #6 look vulnerable. They could be damaged from blown tires or when mechanics climb on the wheels.

7. BIT light could be eliminated by having gauge read 500 + for failed wheel circuit or if digital indicator is FFF. A fail light in the corner should be on to alert the problem.

8. Need master caution hookup for tire pressure failure light.

9. During RTO performance, it was able to pick out pressure loss before ground. Initial pressure loss quite slow but sped up once below 200 psi.

(3) Percent Tire Load via Bogie/Axle Strain

A. SYSTEM DESCRIPTION

The "weight and balance" approach to Low/Failed tire detection consists of comparing transducer signals associated with pairs of wheels - the fore or aft pair on a main gear bogie, for example.

The differences between transducer signals (indicated loads) for each pair of wheels are chiefly proportional to the tire pressure differences (see Figure 15). For the DC-10 style main gear bogie-mounted transducers, the proportionality factor depends on the specific gear dimensions, the torsional stiffness of the bogie beam and the compliance characteristics of the tires. In practice, relatively large differential deflections exist between the measurement points on opposite sides of the bogie/axle as a result of differential tire pressures.

Differential deflections also occur from other causes such as:

- o Various static loading distributions and quantities of fuel, cargo and passengers.
- o Runway and taxiway crown, roughness, and undulations.
- o Inertial side forces in turns, crosswinds, and the like.
- o Tire scrubbing during turns; especially slow, tight turns.

Airframe structural dynamics also enter into the picture when the aircraft is moving. These are primarily low frequency effects as the natural frequencies are quite low.

Thus, the system must provide moderately sophisticated signal processing capable of recognizing the various gear loading patterns and differentiating between those which are caused by differential tire pressures and those which result from the various dynamic and inertial forces which are reacted through the bogie-beam/axle members. This signal processing occurs in a number of categories:

- o Higher frequencies are filtered through a combination of transducer frequency response, demodulator, and A/D converter characteristics.
- o Software digital filters smooth the data before it is entered into the comparison routine.
- o Upon indication that an alarm condition may be present, the signatures associated with the various inertial and turning forces are looked for, and if present, the alarm is inhibited.

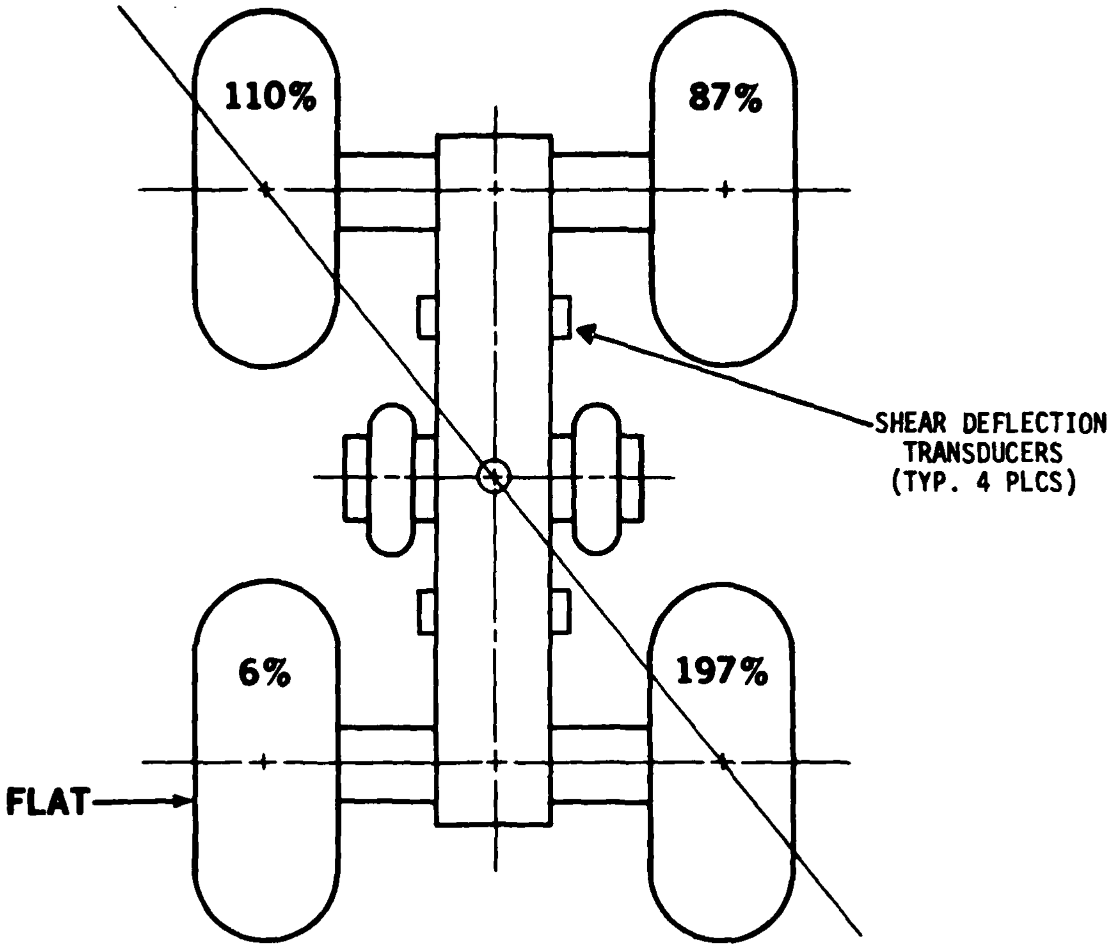


FIGURE 15
PERCENT TIRE LOAD SYSTEM
LOAD DISTRIBUTION CHANGE DUE TO LOW TIRE

- Various other alarm criteria and time delays are also applied, depending upon such factors as the magnitude of the differential load, the aircraft weight, etc.

The TIRE MONITOR measures the load on each tire relative to the load on the companion tire on the same axle. The 3-digit display indicates the load carried by the selected tire in percent. When 100 percent is displayed, the selected tire is carrying its full share of the shared load. When values less than 100 percent are indicated, the selected tire is carrying less than its share of the load. Values greater than 100 percent are indicated when the selected tire is carrying more than its share of the load. Refer to Figure 16 which shows the cockpit display/control unit.

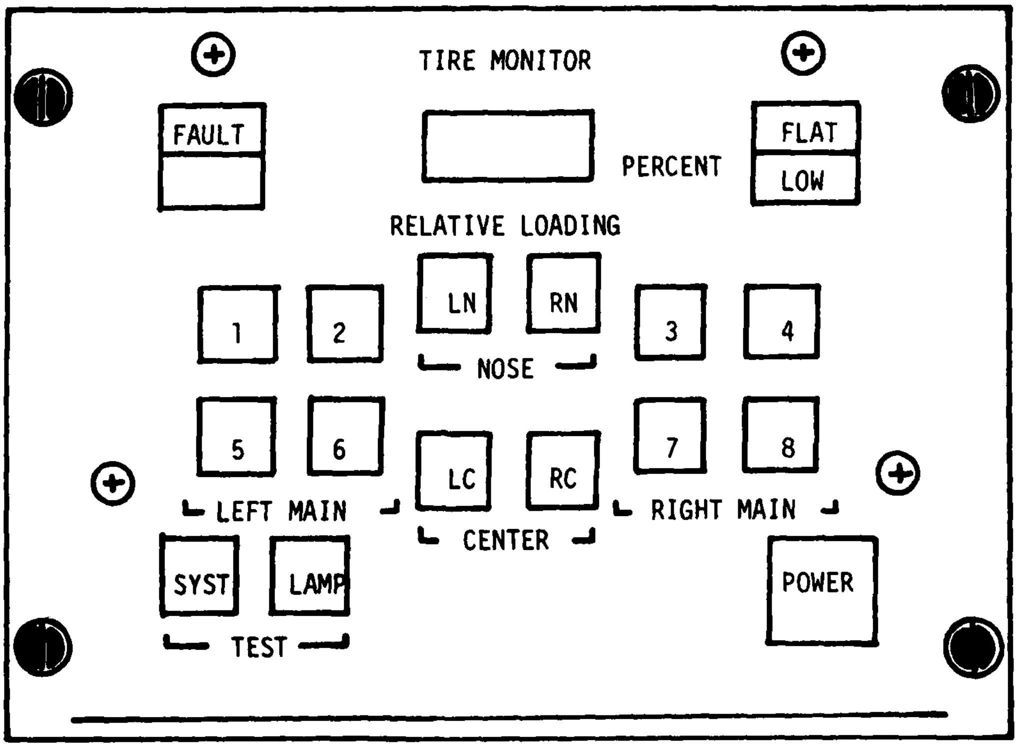


FIGURE 16

COCKPIT DISPLAY, SYSTEM 3

In normal operation when energized, the system continuously scans the transducer outputs and calculates the tire loads comparing them against alarm limits. Each scan requires about 60 milliseconds. In the normal scanning mode, the digital display screen is blanked and only the "POWER" switch is illuminated.

Filtering is provided to eliminate spurious trips which might be caused by short-term electrical and/or load transients. In addition, an alarm condition must be present on three successive scans to trip the actual alarm lights and/or signals which will alert the aircraft crew of any abnormal tire loading condition.

Two adjustable levels of alarm conditions are provided. The first level is activated when a load unbalance of ± 15% is detected. In this condition, the display annunciator labeled "LOW" is illuminated. Simultaneously, the pushbutton switch associated with the tire which indicates a low load illuminates to identify the offending tire to the crew. (NOTE: The 15% threshold was increased during flight test to avoid false warnings when aircraft was rolling.)

If the load unbalance should continue to increase (associated with decreasing pressure in the offending tire) to or beyond the second trip level (50%), the "FLAT" annunciator (top half of "FLAT/LOW" annunciator screen) will illuminate. In addition, the location switchlight will change from steady to flashing condition.

In the "FLAT" alarm condition, the "LOW" light will also continue to be illuminated. At any time that either of the "LOW/FLAT" lights are on, one or more remotely located alarm lights can be illuminated also.

Any alarm condition will continue to be indicated by the display so long as it persists. Should the condition which caused the alarm disappear, or be corrected, the system will automatically reset to the normal scanning mode.

Multiple alarm conditions (affecting more than one tire) can also be detected and displayed by the system in the same manner as for a single alarm condition.

The system can be energized continuously. It functions in the tire monitoring mode when the aircraft is on the ground - parked, taxiing, and during the takeoff and landing rolls. However, alarms are disabled whenever the total measured loads on the gear/tires are less than 5-15 percent of the aircraft empty weight values and/or a ground speed exceeding 100 knots is sensed (based upon an input signal derived from a wheel speed sensor - from the antiskid system). A cockpit mounted display panel is shown in Figure 17.

Manually Initiated Tire Load Indication

Tire loading readings can be initiated manually at any time the aircraft is on the ground and the gear is reasonably loaded (equivalent to 50% of aircraft empty weight or more). This is accomplished as follows:

1. Press the switch button on the cockpit display associated with the tire load reading wanted.

2. The switch button will illuminate when activated and the digital display will come on indicating the relative loading on that tire.

FIGURE 17. COCKPIT-MOUNTED DISPLAY PANEL

3. The display will continue to monitor the selected tire until one of the following occurs:

   (a) The selected tire switch is pressed again.

   (b) Another tire channel is selected by pushing the appropriate switch.

B. LABORATORY TEST RESULTS

(No Lab Tests were performed with this system due to the difficulty of simulating gear installation and loading.)

C. INSTALLATION

Transducer Installation

The transducers were installed on the left gear only of the test DC-10 by maintenance personnel using an installation procedure provided by the manufacturer. The installation sequence and working times were as follows:

- Preparation - including cleaning of paint from mounting lugs, installation of cover brackets and setup of installation test equipment - 1 manhour.
- Aircraft jacking - 30 min. elapsed, 2 manhours.
- Transducer Installation - 4 transducers, including verification of lug dimensional accuracies, shimming, attachment and torquing - 1 manhour.
- Cover installation - .25 manhour.
- Lowering Aircraft from jacks - 30 min. elapsed, 2 manhours.
- Cable routing, attachment to structure, and connection to aircraft wiring (previously installed) - 1 manhour.

No problems were encountered during any of this sequence - the transducer installation was straight-forward and relatively easy.

As there were no transducer failures during the flight test, there was no quantitative test of removal/replacement of a single transducer. Estimated time, based upon experience is less than one manhour.

NOTE: Aircraft jacking is not required for any routine replacement/maintenance of the transducers - only for a new installation or a complete replacement of all the transducers on a bogie. In addition, the "fly-to-zero" routine (Automatic Inflight Zeroing) is optional to jacking.

The transducer installation is relatively simple. Since there are no wheel connections involved, changing the tire will not disturb the system. Thus, no wheel and tire modification is needed.

The first installation of the transducer will consume more time. With the transducers mounted, shims may need to be added to zero the transducer readings. The addition of shims is required to take out any unevenness in the lugs which may create non-zero reading. However, once the necessary shims are added, transducers become interchangeable. The same transducer is used at all wheel installations including nose installation. Typical transducer installations during the flight test are shown in Figures 18 and 19.

1. System Calibration

Two approaches to establishing initial transducer zeros were tested successfully.

(a) The aircraft was jacked at the wing jack points to unload the gear during or after transducer installation. The auto-zero routine was initiated manually as part of the installation/calibration procedure.

(b) The aircraft was flown and the auto-zero routine initiated manually with gear down at less than 200 knots, to establish the initial zero values. (Subsequently, the normal auto-zero routine takes place automatically.)

2. Once zeros were established in the computer memory, the system was calibrated as follows:

(a) With all the tires on the gear at ambient temperatures, adjust all tire pressures to their rated pressure (± 1 psi).

(b) While maintaining the tire pressures constant, adjust the computer scaling factors for each transducer output to obtain readings of 100% ± 2% on all channels (1, 2, 5, and 6) on the cockpit panel.

D. FLIGHT TEST RESULTS

Statically, the tire load responded to the tire pressure very closely. Per the static bleeding tests shown in Figures 22 and 23, the transducer output provided excellent results. However, usable digital readout data was never obtained while the aircraft was in motion. Initial false alarms occurring with the aircraft moving were eliminated and valid low tire alarms could be obtained with the aircraft in motion.

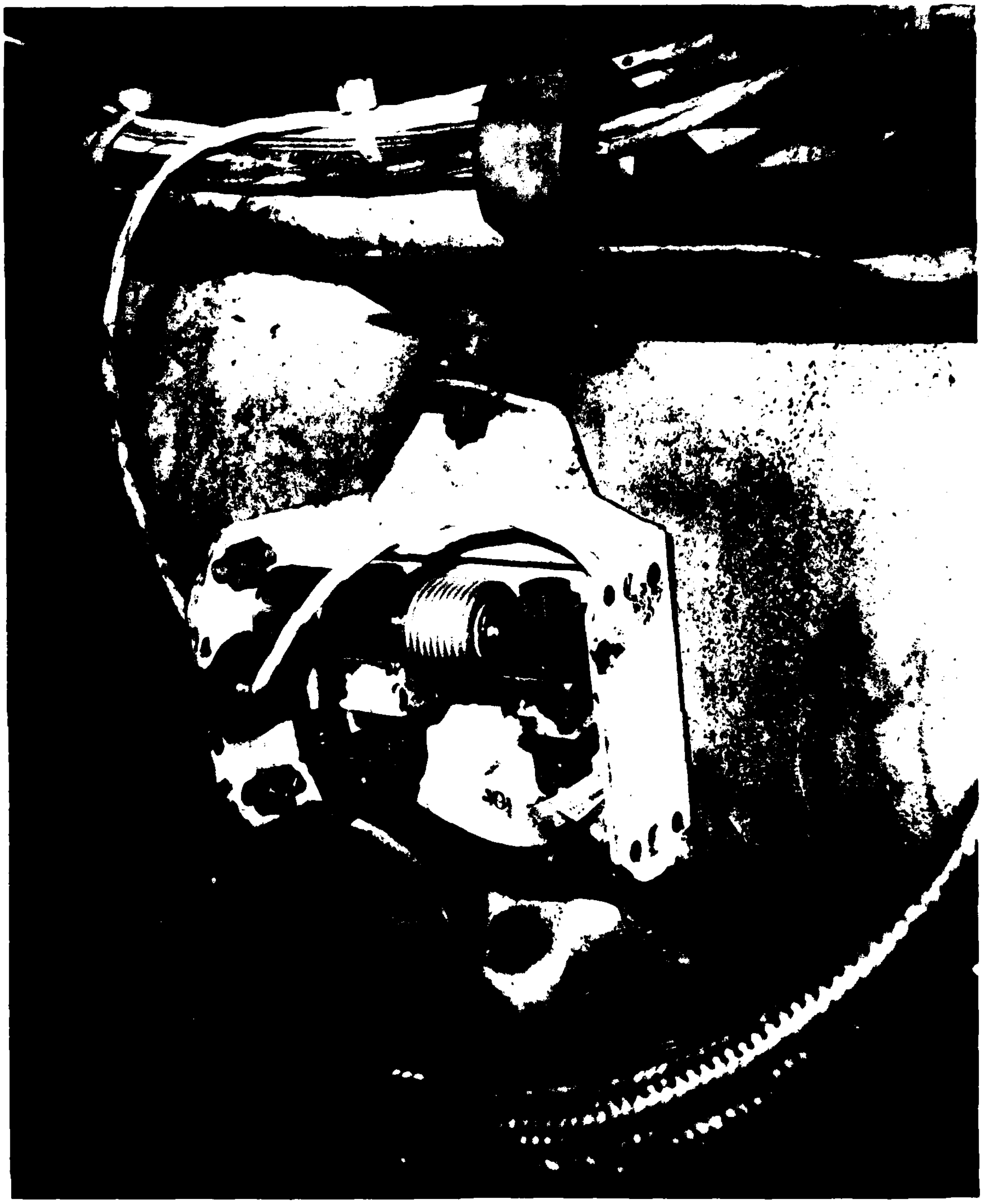


FIGURE 18. TRANSDUCER INSTALLATION VIEW

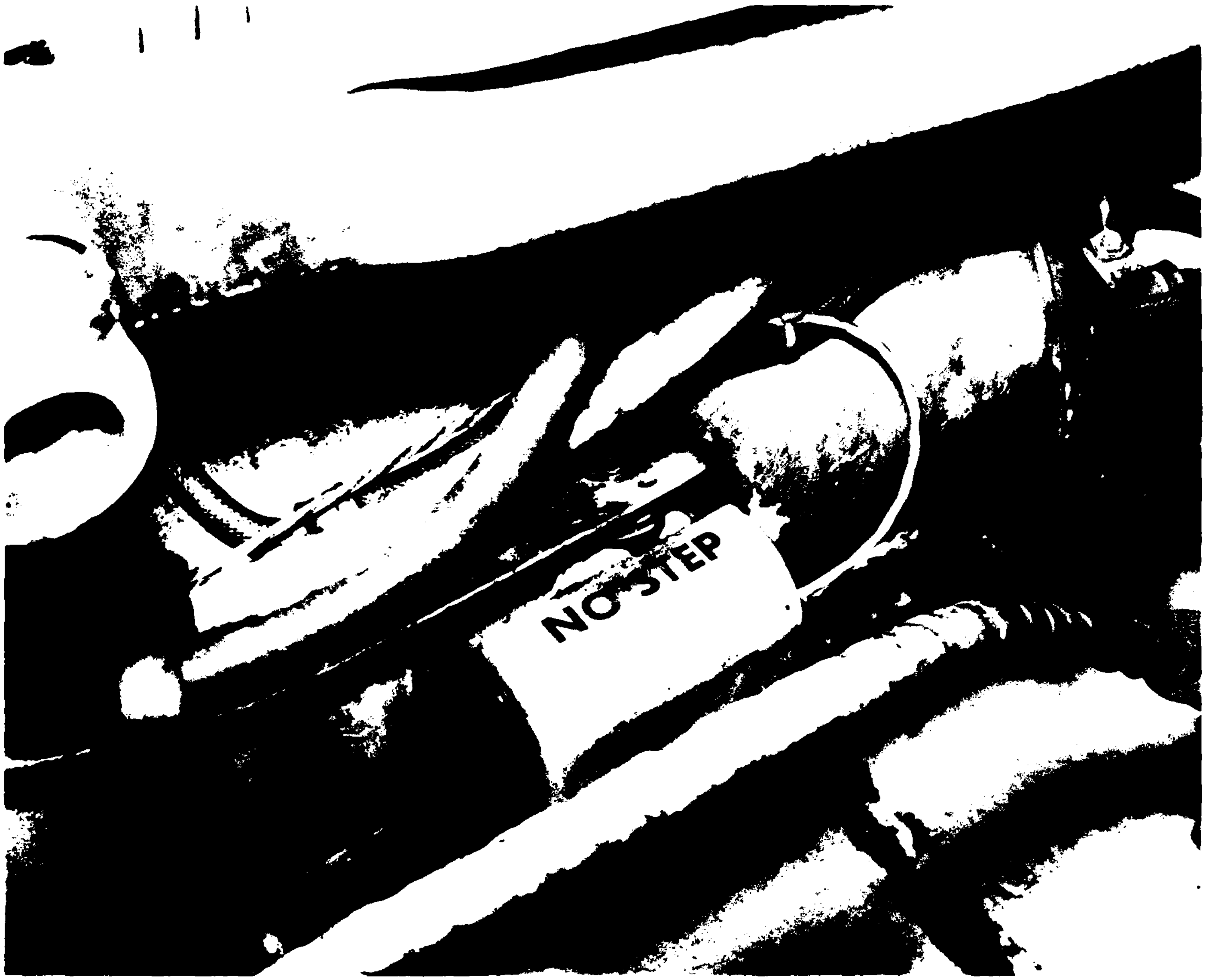


FIGURE 19. TRANSDUCER INSTALLATION WITH TRANSDUCER COVER ON

During an RTO three tires went flat after the aircraft came to a rest. The heat generated within the brakes conducted to the wheels resulting in melting of fuse plugs and deflation of the majority of the tires. Fuse plugs melted shortly after the aircraft stopped on the runway, the first tire started leaking, becoming completely flat 3-1/2 minutes later. The second tire fuse plug blew 4 minutes after the first tire. The third tire was not detected since the loads on that axle re-equalized. Even though this is a rare case, if two tires on the same axle happened to be blown at the same time the system could not detect this failure.

The system hardware including transducers and computer did not fail throughout the flight test program. An intermittent connection on a connector to a component in the display was encountered early in the test program and corrected.

The software in a system such as this must be quite sophisticated to provide reliable low tire warnings. The key to avoiding false failure warnings lies in the ability of the software routines to recognize transducer loading patterns across the airplane and reject load differentials caused by runway crown, runway unevenness, turning, gear side loads, and other normal operational effects causing differential wheel loads. The software required extensive development during the flight test program to account for these effects with significant progress being made in the short 2 month test program. Most attention was required to handle dynamic loading variations. Further software development will be required before production status hardware is developed.

Static Tests

A static bleed test was performed on all four tires on the left main landing gear while the aircraft was on scales. The pressure of each tire was gradually reduced in increments down to the point where the wheel scales reached their maximum weight limit. During the bleed test on each tire, the pressures in the other three tires were maintained at 190 psi. At each pressure, the following measurements were recorded:

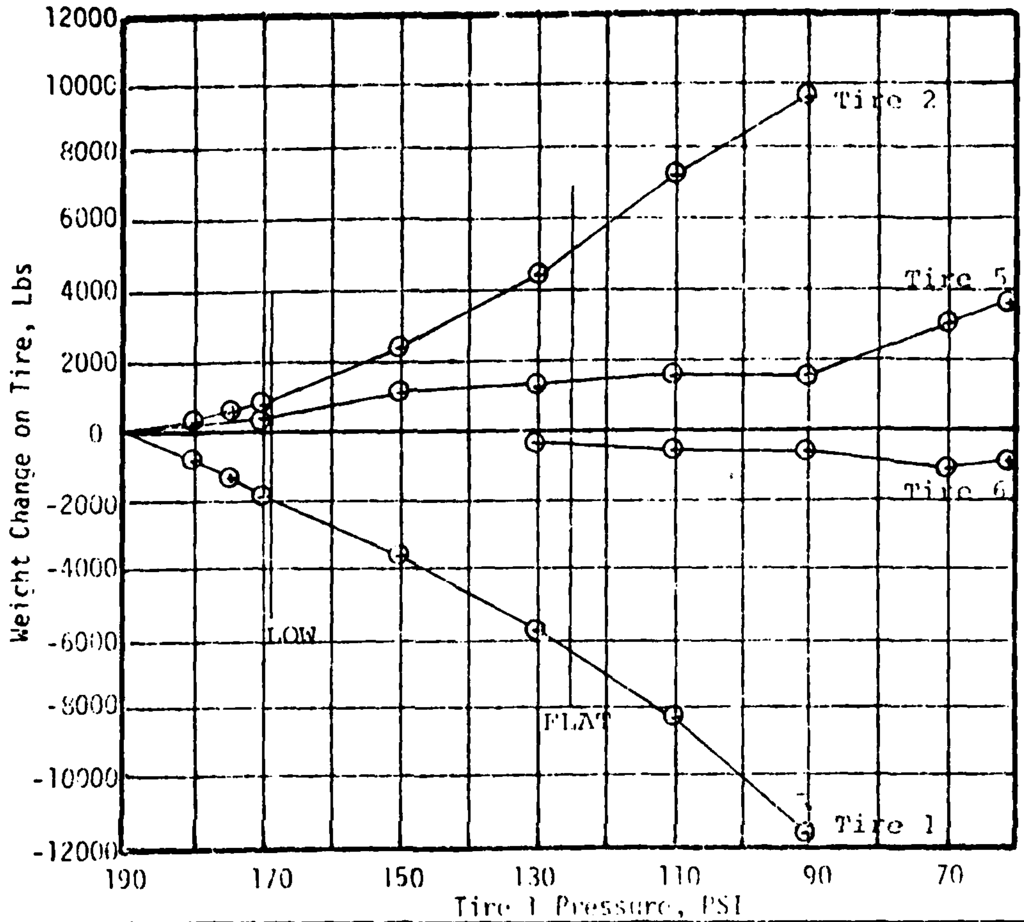
1. Individual scale weight data for each tire.

2. Low Tire monitor readings for each tire.

3. Data system readings from the demodulator output (internal to the computer).

This data versus tire pressure is plotted in Figures 20 through 25 and is tabulated in the tables below the graphs.

These plots all follow a common pattern. Most of the weight is transferred from the tire losing pressure to its companion on the same axle. Twist of the bogie causes some increase in load on that axle. Some shifting of the loads on the other gears also occurs, primarily a rocking action on the center gear increasing its load. Actually, this rocking action usually lightens the load on the right main gear.

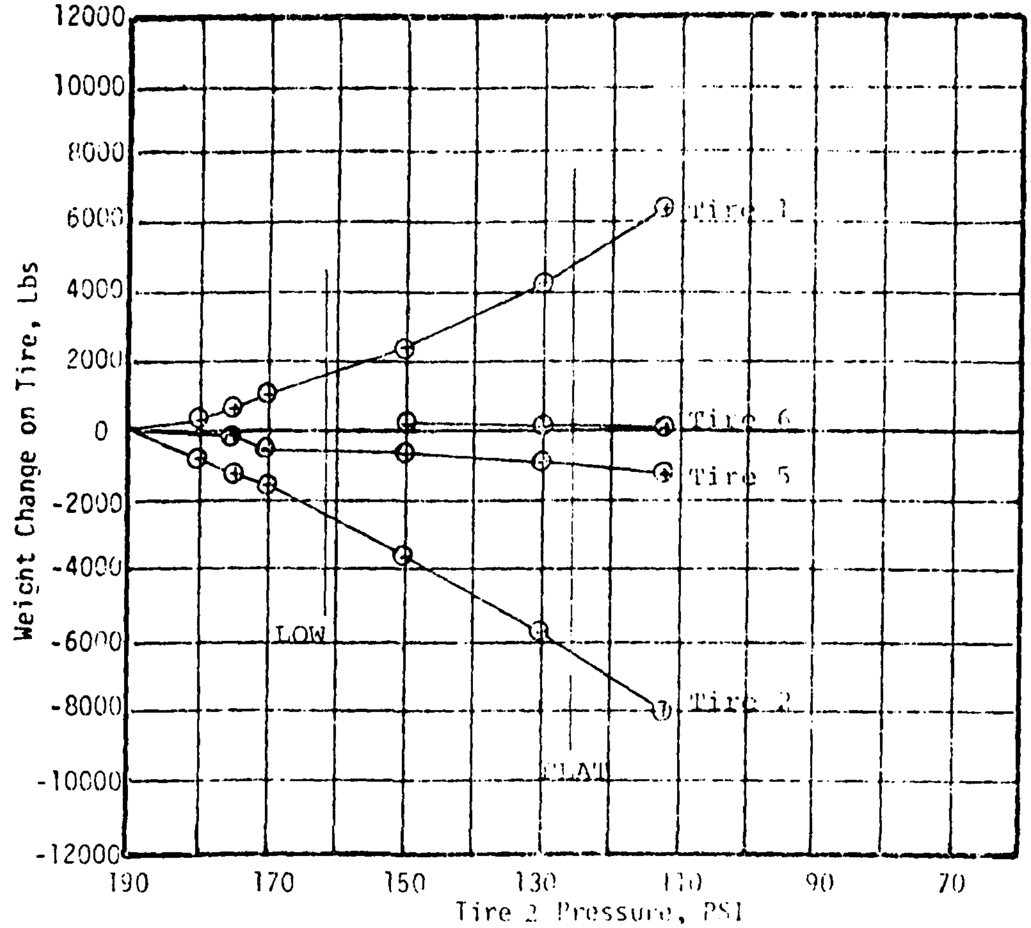


TIRE 1 Pressure, PSI	INDIVIDUAL WHEEL WEIGHT, LBS				DELTA WEIGHT CHANGES, LBS			
	Tire 1	Tire 2	Tire 5	Tire 6	Tire 1	Tire 2	Tire 5	Tire 6
190	44600	38330	43320	39350	44600	38330	43320	39350
185	44590	38390	43670	39280	-10	60	350	-70
180	43910	38750	43630	39380	-690	420	310	30
175	43350	39000	43750	39420	-1250	670	430	70
170	42750	39230	43850	39460	-1850	900	530	130
150	40990	40880	44570	39380	-3610	2550	1250	30
130	38820	42900	44640	39070	-5780	4570	1320	-280
110	36210	45590	44970	38780	-8390	7260	1650	-570
90	32940	47990	44930	38690	-11660	9660	1610	-660
70	29930	52620	46400	38200	-14670	14290	3080	-1150
61	28450	54750	46940	38360	-16150	16420	3620	-990

Notes:
- Total Gross Weight at 445,750 lb
- Assymetric loading outboard to inboard tires—10,240 lbs total
- Left Main Gear unloads a total of 2900 lbs, transferring load to other gear (primarily the centerline gear).

FIGURE 20

DEFLATION TEST, TIRE PRESSURE VS. WEIGHT CHANGE ON TIRE #1

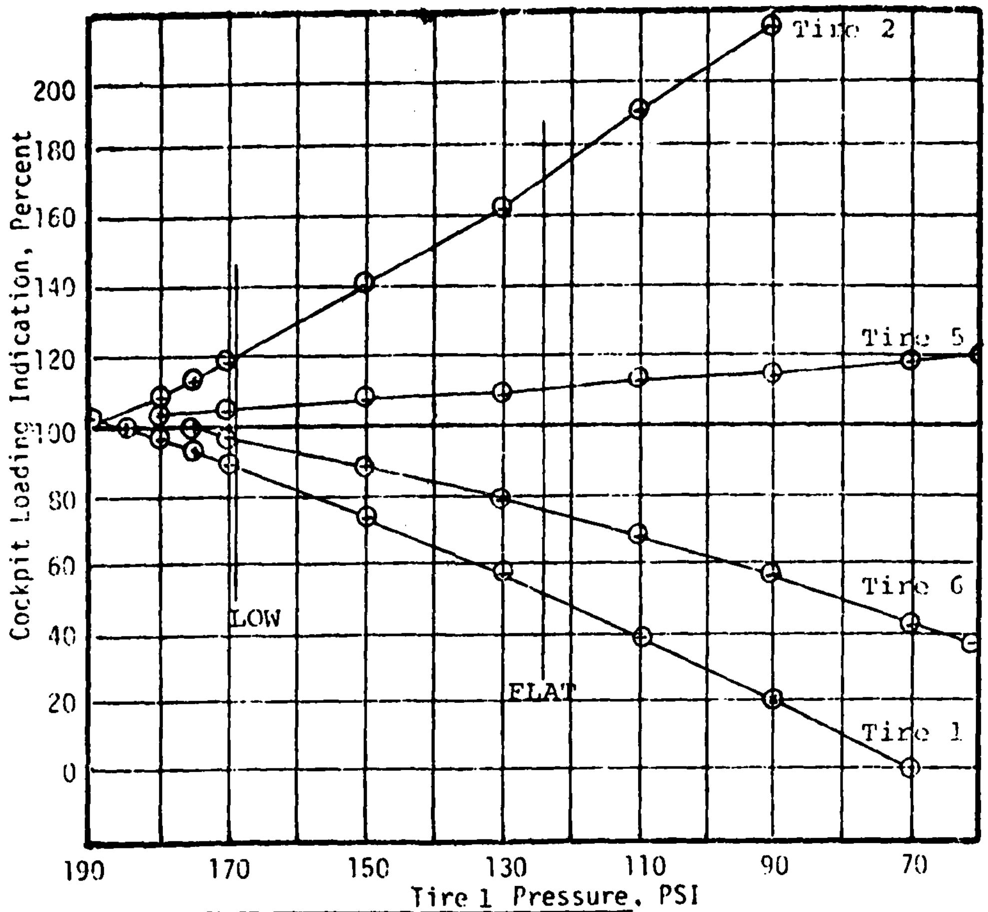


TIRE 2 Pressure, PSI	INDIVIDUAL WHEEL WEIGHT, LBS				DELTA WEIGHT CHANGES, LBS			
	Tire 1	Tire 2	Tire 5	Tire 6	Tire 1	Tire 2	Tire 5	Tire 6
190	48570	43950	50300	43690	48570	43950	50300	43690
185	48690	43890	50370	43850	120	-60	70	160
180	48980	43180	50470	44000	410	-770	170	310
175	49190	42700	50220	43920	620	-1250	-80	230
170	49740	42400	49770	43600	1170	-1550	-530	-90
150	51100	40310	49690	43840	2530	-3640	-610	150
130	52940	38150	49380	43810	4370	-5800	-920	120
112	54930	35890	49040	43770	6360	-8060	-1260	80

Notes:
- Total Gross Weight at 496,450 lb.
- Assymetric loading outboard to inboard tires—10,240 lbs total
- Variations between gears during bleed—Left main decreased 2880 lb, Center increased 3410 lb, Right main decreased 910 lb, Nose increased 720 lb.

FIGURE 21

DEFLATION TEST, TIRE PRESSURE VS. WEIGHT CHANGE ON TIRE #2



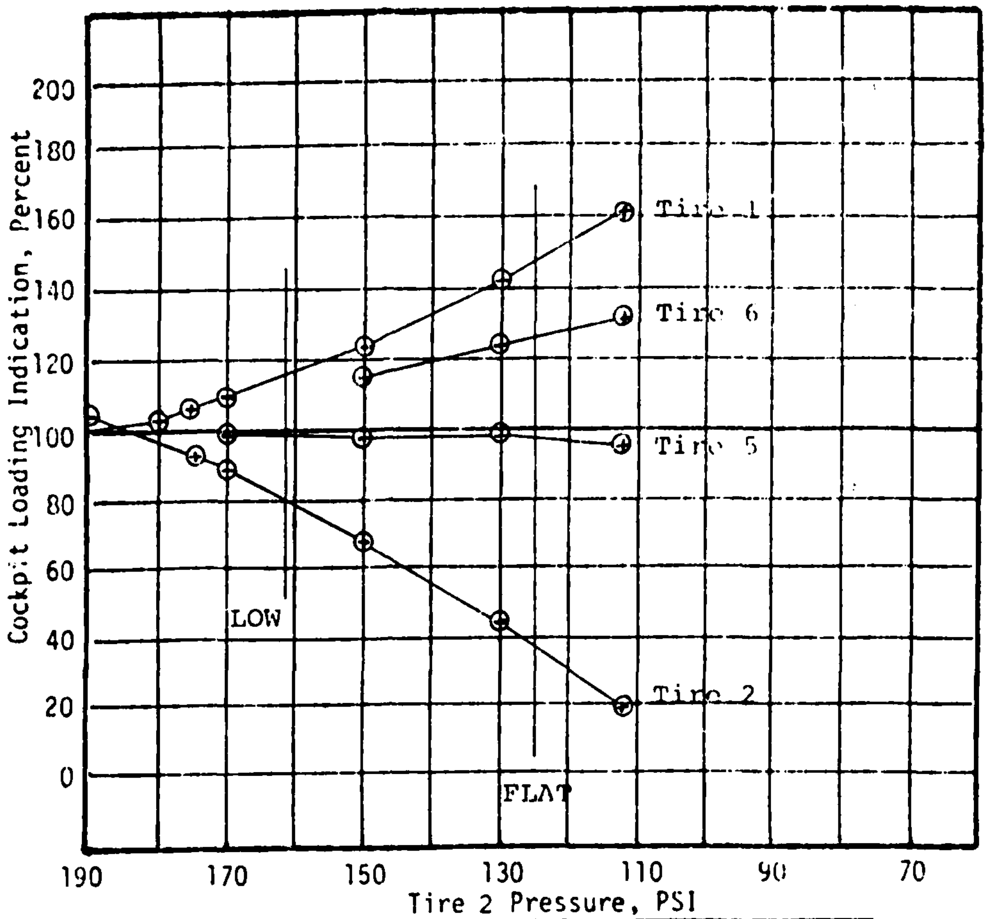
Tire 1 Pressure, Psi	COCKPIT LOADING INDICATION PERCENT			
	Tire 1	Tire 2	Tire 5	Tire 6
190	102	101	103	102
185	99	103	103	101
180	96	108	103	100
175	93	113	103	99
170	89	118	104	97
150	73	140	107	88
130	57	163	109	79
110	39	189	112	67
90	20	217	114	56
70	0	251	118	42
61	0	264	120	36
169	91	118	103	96

Notes:

- Pressures at start of test 190 ±2 psi
- LOW Alarm Light at 169 psi, FLAT light at 124 psi
- Pressures at end of test 183 ±1 psi except Tire 1 at 169 psi

FIGURE 22

DEFLATION TEST, TIRE PRESSURE VS. COCKPIT LOADING INDICATION (#1)

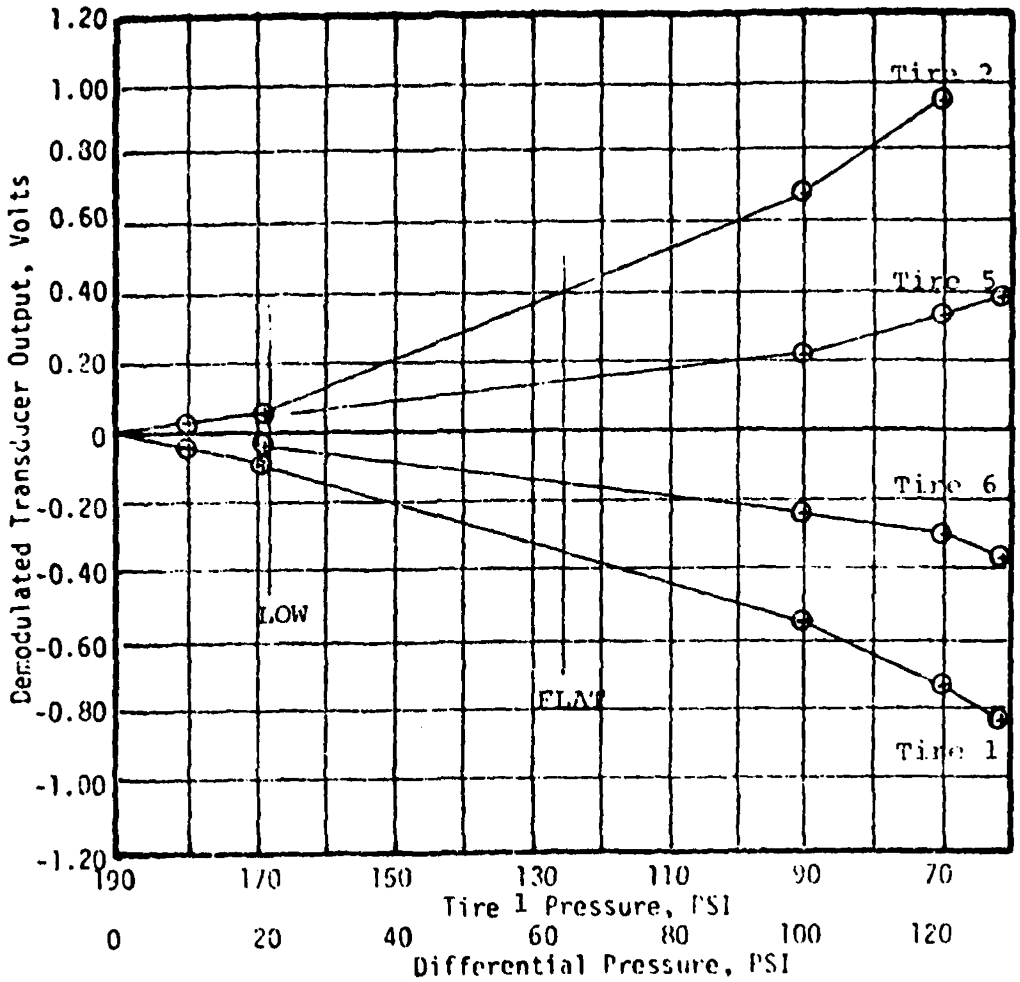


Tire 2 Pressure, Psi	COCKPIT LOADING INDICATION PERCENT			
	Tire 1	Tire 2	Tire 5	Tire 6
190	99	104	101	103
185	100	103	101	104
180	104	97	101	106
175	107	93	100	108
170	111	89	99	110
150	125	68	98	116
130	142	44	97	124
112	161	19	96	133

Notes:
- LOW Alarm Light at 162 psi
- FLAT Alarm Light at 125 psi
- Reached weight limit of 55,000 lb on Wheel 1 at 112 psi

FIGURE 23

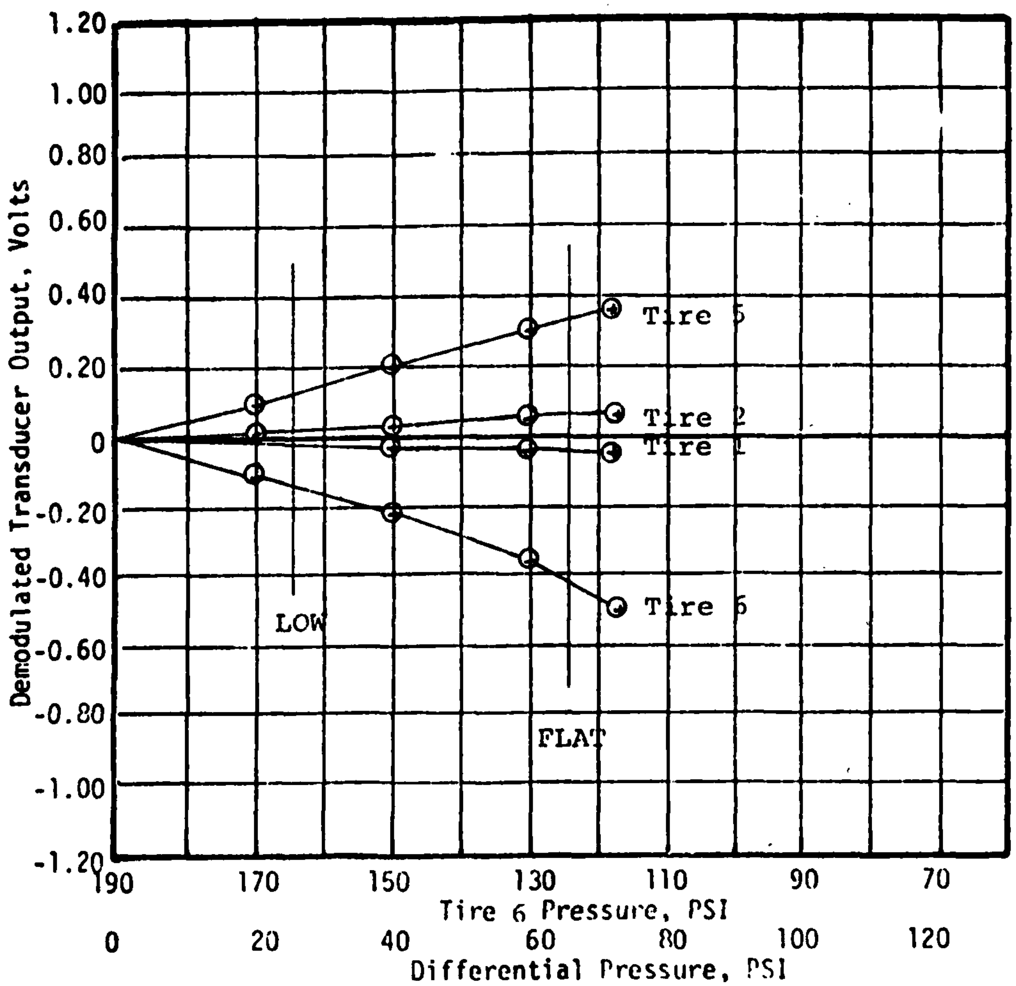
DEFLATION TEST, TIRE PRESSURE VS. COCKPIT LOADING INDICATION (#2)



Tire [illegible] Pressure	DEMODULATED TRANSDUCER OUTPUT, VOLTS			
	Tire 1	Tire 2	Tire 5	Tire 6
190	.89	.57	1.02	1.60
185	.87	.58	1.02	1.60
180	.85	.60	1.02	1.60
169	.80	.63	1.02	1.56
90	.33	1.24	1.24	1.36
70	.15	1.50	1.35	1.29
61	.05	1.62	1.40	1.23

FIGURE 24

DEFLATION TEST, TIRE PRESSURE VS. DEMODULATED TRANSDUCER OUTPUT (#1)



Tire 6 Pressure	DEMODULATED TRANSDUCER OUTPUT, VOLTS			
	Tire 1	Tire 2	Tire 5	Tire 6
190	.86	.74	1.26	1.56
170	.86	.75	1.35	1.46
150	.84	.78	1.46	1.34
130	.82	.80	1.58	1.19
117	.81	.81	1.64	1.14

FIGURE 25

DEFLATION TEST, TIRE PRESSURE VS. DEMODULATED TRANSDUCER OUTPUT (#6)

Asymmetric loading of the inboard/outboard tires on the left main was also noted in most of the data taken on the left main gear. On the average, the outboard tires were loaded 10 percent more than the inboard tires with the aircraft on a flat surface. On a normal runway crown the load is equalized.

Tire Deflection After Rejected Takeoff

The data in Figure 26 shows the results of tire deflation after a 75% energy rejected takeoff when fuse plugs melted. The approximate system alarm points are shown on the figure where wheel #5 goes first followed by the increase in load on #6 tire. Sometime later tire #1 starts losing pressure causing its load to be transferred to tire #2.

Dynamic Test Results

The bogie mounted transducers measure the total strain deflection of each side of the bogie. The strain deflection is the summation of both vertical shear strain (due to supporting the weight of the aircraft) and rotational strain due to moments applied with respect to the longitudinal axis of the bogie.

Rotational moments applied to the bogie are caused by several forces. Of primary interest is the torque induced by one tire having lower pressure than its mate. Because of the nearly linear pressure compliance of the tires, pressure reduction in one tire with respect to the other results in a nearly linear moment applied to the bogie tube. The difference in the strain deflection of the transducers is a linear indication of the torque on the bogie and therefore the differential tire pressure.

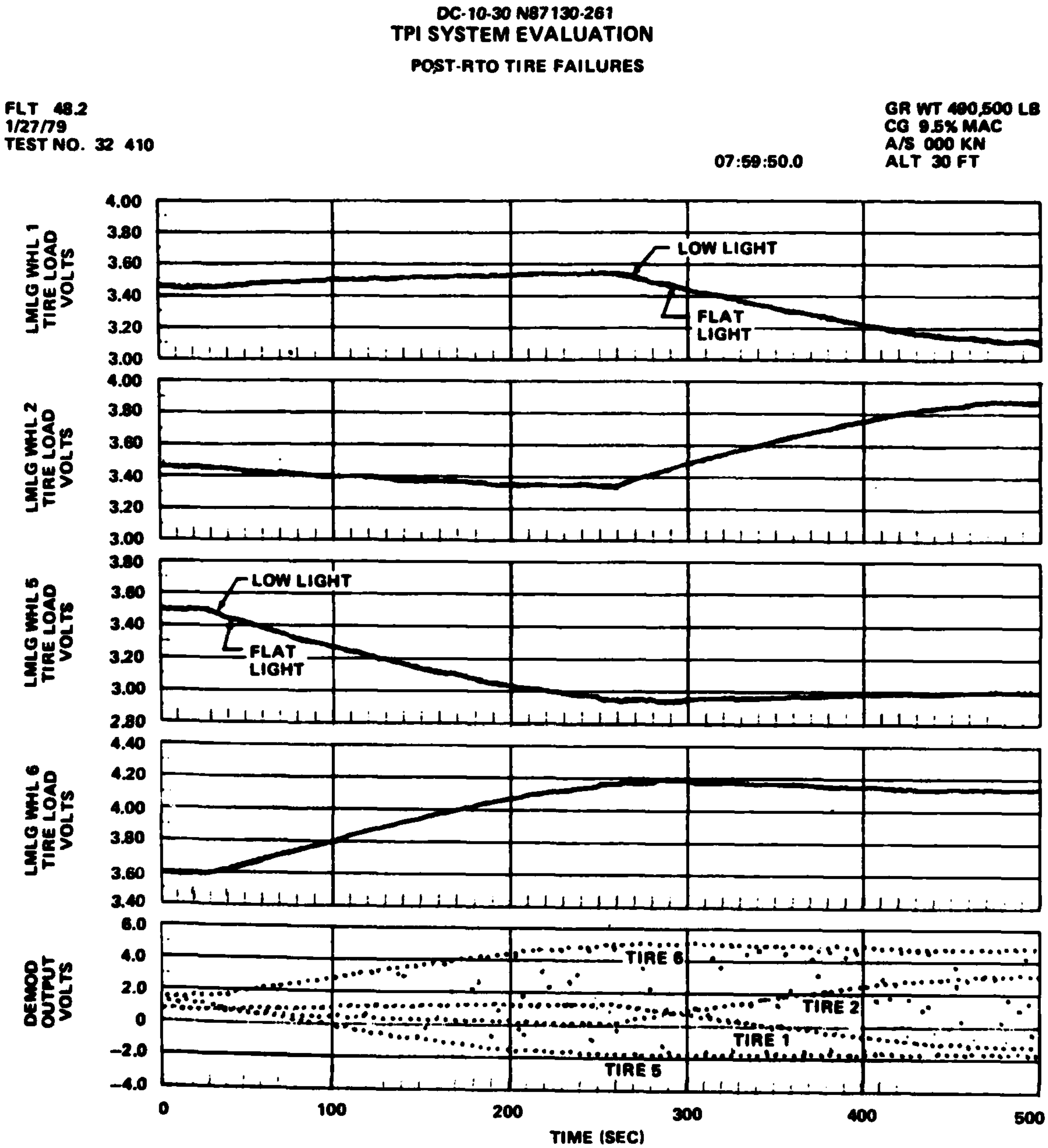
Other sources of torque on the bogie result from scrubbing effects during turning and due to side loading of the landing gear either due to turning at high speed or from relative side motion of one landing gear with respect to the other. This last torquing effect occurs because of the compliance of the aircraft frame, particularly between the landing gear attachment points.

Turning Signatures

Turning effects have unique signatures different from that of a low tire.

Figure 27 shows typical signatures of turns during low speed taxi operations. This data was taken during taxi to parking after the last test flight landing.

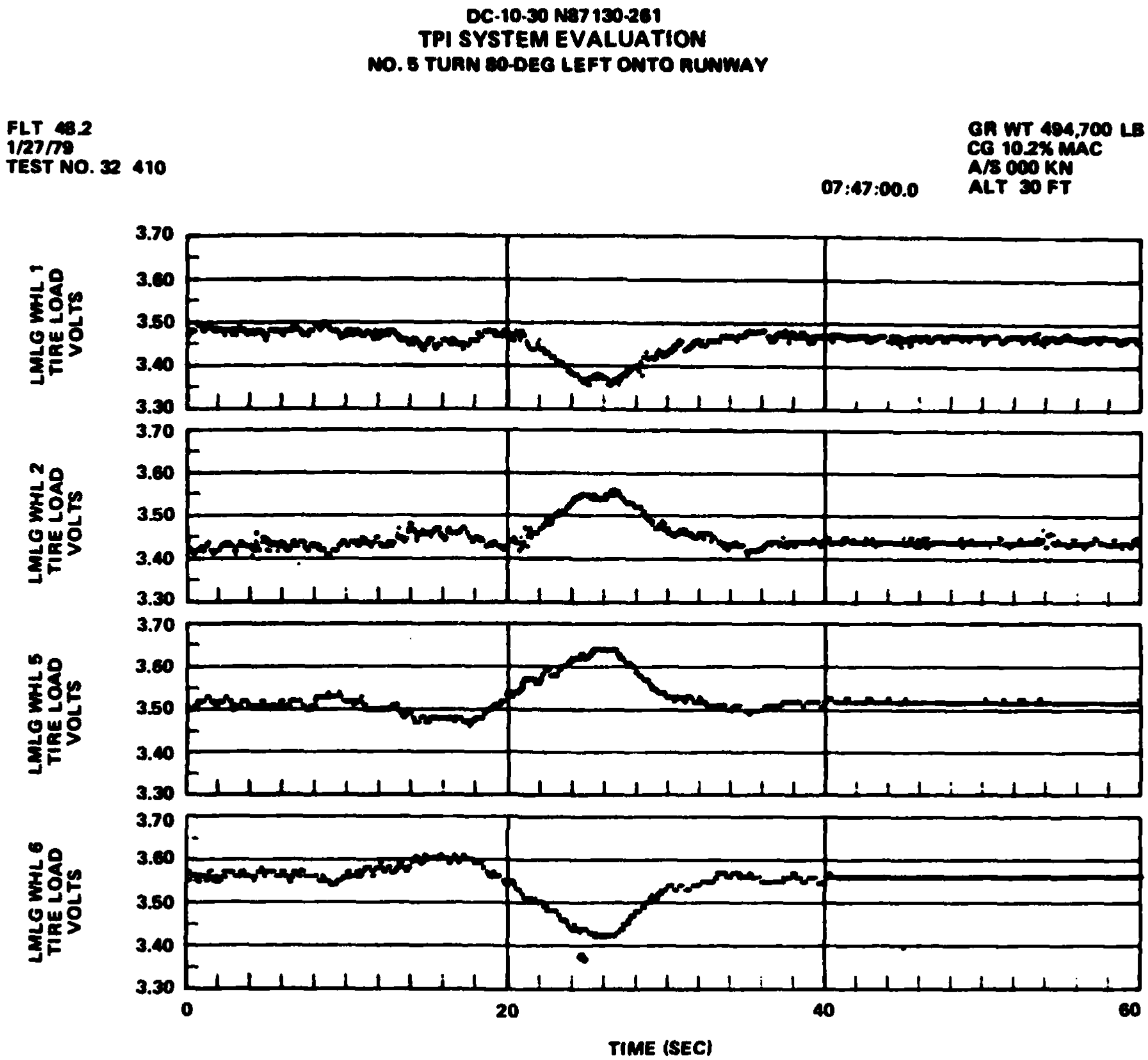
False tire monitor alarms were eliminated during turns by providing a software routine which recognized the turning pattern signature - locking out the alarm when the turning pattern occurred.



SEQUENCE OF EVENTS

- FUSE PLUGS MELT SHORTLY AFTER AIRCRAFT STOPS ON RUNWAY
- TIRE 5 STARTS LEAKING, BECOMING COMPLETELY FLAT 3.5 MINUTES LATER
- TIRE 5 LOW LIGHT ALARM LIMIT REACHED 5 SECONDS AFTER BLOWOUT. FLAT LIGHT ALARM LIMIT REACHED 20 SECONDS AFTER BLOWOUT
- TIRE 1 PLUG BLOWS 4 MINUTES AFTER TIRE 5. LOW ALARM LIMIT REACHED IN ABOUT 25 SECONDS, AND FLAT LIMIT IN ABOUT 30 SECONDS

FIGURE 26. SYSTEM OPERATION DURING TIRE FAILURE FOLLOWING RTO TEST



<u>AMPLIFIED TURNING PATTERN SIGNAL TRACE</u>

- TIGHT-RADIUS LEFT TURN BEGINS AT 17 SECONDS ON PLOT AFTER SLIGHT RIGHT-HAND SWING
- TRANSDUCERS MOUNTED ON LEFT MAIN GEAR MEASURE THE TURNING TORQUE-PRODUCED DEFLECTIONS
- SYSTEM COMPUTER SOFTWARE ROUTINE RECOGNIZES THE TURNING PATTERN AND INHIBITS TIRE ALARM UNTIL THE TURN IS COMPLETED

FIGURE 27. TYPICAL TURNING SIGNATURES

Operation During Takeoff Roll

Figure 28 shows the last ten seconds of a takeoff roll followed by the first ten seconds of post-rotation climbout. Some flight test data system noise is present on the Tire 1 and 2 channels. Disregarding the data system noise, the predominant dynamic signal noise induced by the runway is about 1 Hz or greater with amplitudes up to 30% of the fully loaded gear values.

Most of the fluctuations in the individual transducer signals are in phase indicating that they may be caused by "up and down" airframe flexing. However, some fluctuations are observed which indicate side loading. These are of magnitudes similar to the "up and down" fluctuations and at frequencies of about 1 Hz also.

It was determined from this data that filtering the transducer signals with a second order filter with a corner frequency of about .15 Hz would eliminate nearly all of the "noise" caused by the interaction between the aircraft and runway during the takeoff roll. The system was revised to incorporate these filter characteristics just prior to the final test flight.

Side Loading Effects

Side loads of three different kinds were observed during the flight test. The first of these is the asymmetric loading between inboard and outboard tires. Its values were on the order of 10% in terms of heavier loading on outboard tires. Since this type of side load tends to be biased out in the system calibration, its effects are reduced to values equivalent to 5 or 10 psi tire pressure differentials. However, as this asymmetric loading pattern results from camber built into the gear to accommodate runway crown, some further data on the loading pattern on typical runways as contrasted to typical parking areas is needed.

A second type of side loading involves the up/down flexing of the airframe. This is taken care of by filtering and smoothing of the data.

A third category of side loading is caused by inertial or wind effects - sideways scrubbing of the gear during a high speed turn or during cross winds. A typical pattern for these is shown in Figure 29. A software routine which recognizes this pattern was implemented in the system and its operation was improved through the use of additional filtering in two subsequent modifications. It was not possible to accumulate much operational time on the final system software so the effectiveness of these modifications could not be evaluated adequately.

DC-10-30 N87130-261
TPI SYSTEM EVALUATION
TAKEOFF

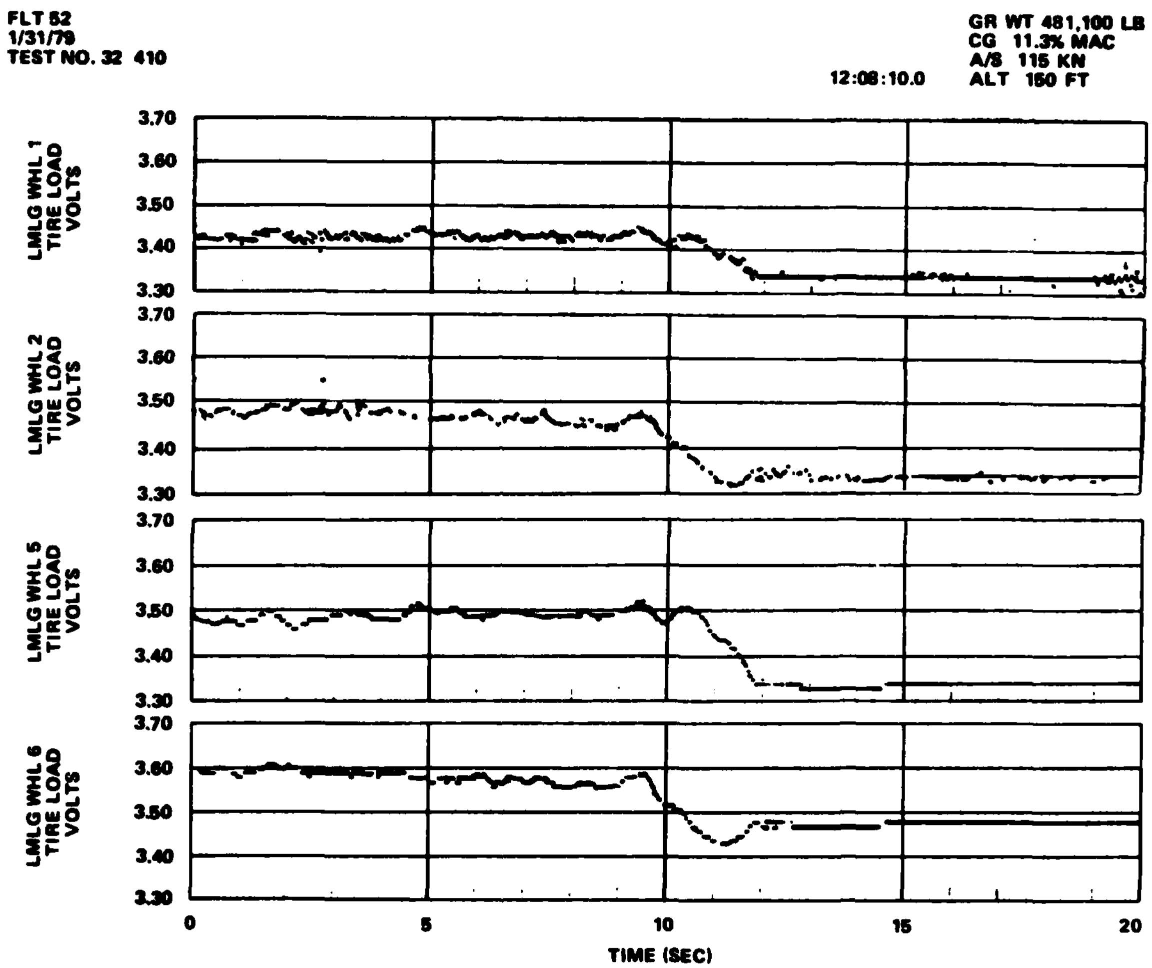
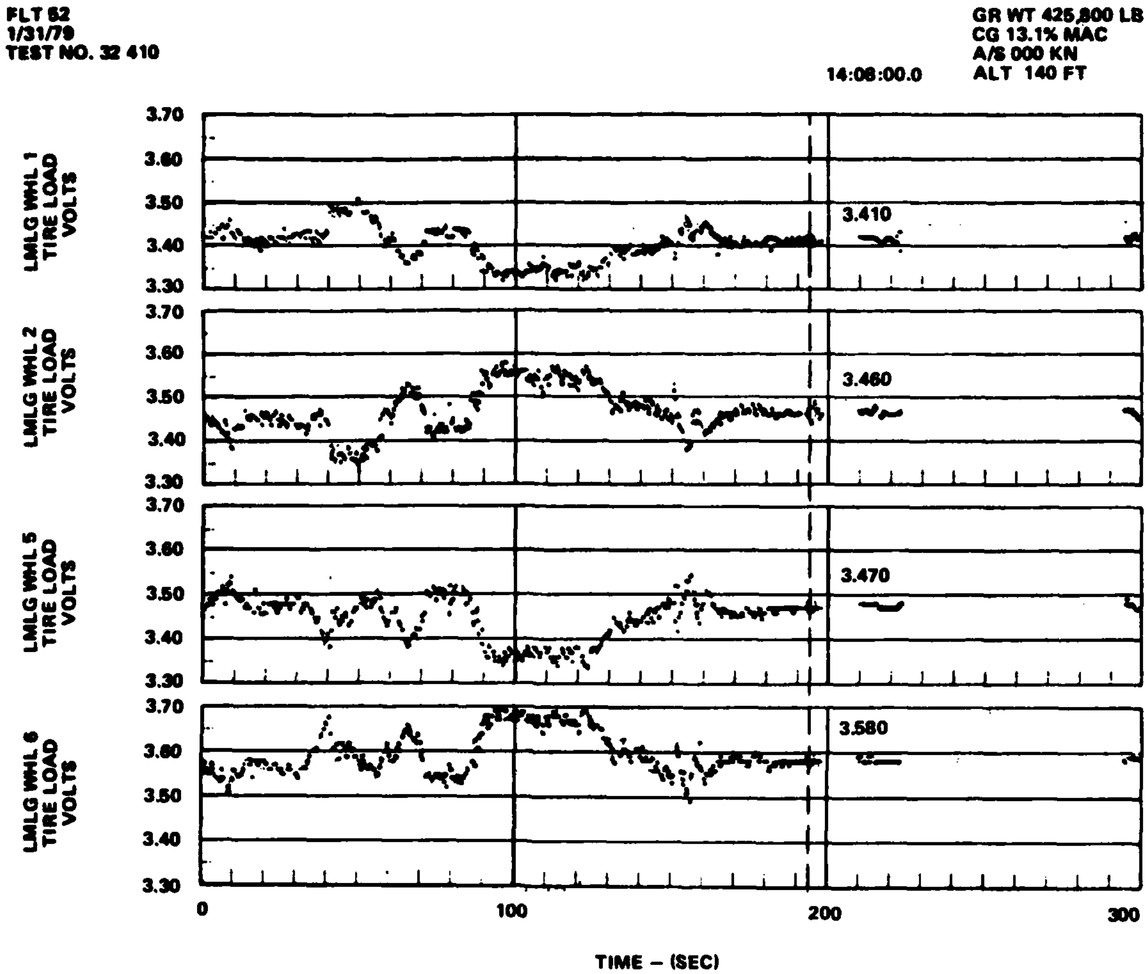


FIGURE 28. TYPICAL TRANSDUCER OUTPUTS DURING TAKEOFF ROLL AND ROTATION/ CLIMBOUT OF AIRCRAFT

DC-10-30 N87130-261
TPI SYSTEM EVALUATION
SIDE LOADS DURING TAXI



- SIDE LOAD PATTERNS ARE OBSERVED AT AROUND 80 AND 100 SECONDS ON THE ABOVE PLOT
- NOTE INVERSION SYMMETRY BETWEEN TIRES ON EACH AXLE
- PLOT SHOWS UNFILTERED TRANSDUCER OUTPUTS FROM TIRES 1, 2, 5, AND 6

FIGURE 29. TYPICAL SIDE LOAD PATTERNS

Combined transient Effects - Ground Operation

Certain combinations of turning and inertial side load effects cannot be distinguished from a low/flat tire using the software routines developed and tested during this flight test. The data collected tends to indicate that these are either short in duration - or when longer, are reacted on both gears in a recognizable pattern.

Those superpositions of dynamic effects which are short in duration are eliminated by the basic filtering of the system.

It is not certain whether longer term superpositions which would pass through the system filtering actually exist. If they do exist with relatively long duration - exceeding several seconds - a pattern recognition routine which uses the data from both main gears will be applied to eliminate false alarms from this cause. Further testing, including the instrumentation of both main gears, will be required to determine the need for and to prove the operation of this feature, if needed.

E. PROBLEMS ENCOUNTERED/RESOLUTIONS

As mentioned in the section on flight test results, the system hardware performed quite satisfactorily. The system software, as might be expected with a brand new system such as this, required significant development all of which was not completed during the test program.

The key complaint of the flight crew centered around the erratic digital percent tire load display. Meaningful data was never obtained with the aircraft in motion which led to significant, and perhaps somewhat unjust, criticism of the system. In a production system there would be no great value in displaying percent tire load with the aircraft in motion. Beyond this, false low tire warnings were eliminated by the end of the test program and the basic ability of the system to provide a low tire detection capability as well as an accurate weight and balance measurement was demonstrated.

The key question is what low tire warning threshold is desired by the airline operator versus what is practical with the errors inherent in such a system with the aircraft in motion. Statically the system can resolve tire pressure differences as low as 5 psi. Dynamically tire underinflation of 50 psi or more may be required to eliminate false warnings. To summarize, the important factors in the error budget for this system are:

1. Runway roughness or surface unevenness statically and during taxi.

2. Differential inboard outboard gear loads due to gear design.

3. Runway crown.

4. Turning and side load rejection capability.

5. Tire load differences due to differences in tire diameters and spring rates.

As it turns out the differences in tire diameters may be the single largest error effect as discussed in relation to the "wheel speed" system in Appendix A. The effects of tire differences may be eliminated in this system (where they cannot be in the wheel speed system) by "zeroing" the weight and balance system after a tire change or after all tires have been inflated equally. This would "build-in" errors due to ramp unevenness but would eliminate the major source of system error. Matching tires on an axle would also help but is unacceptable logistically for many airlines. Although further analysis and tests are needed to finalize this system practical thresholds can be achieved.

To save maintenance time and assure flight safety, the auto-zero routine flight mode is needed. Transducers have to be zeroed before any accurate readings can be taken. While the auto-zero routine for ground mode is time consuming, the flight mode is beneficial.

F. SUMMARY OF THE FLIGHT CREW COMMENTS.

Most of the following comments have been discussed in the text.

1. Couldn't zero the system in flight mode. Aircraft needs to be zeroed by jacking up.

2. Erratic readings on panel during flight.

3. Flight test had commented that "power" switch is not needed. actually the power is supposedly on at all times with the aircraft power on.

4. During airborne, when tire load is being called for, the digital display will illuminate with the error code "U04".

5. Transient problem did exist during the early part of the flight program. However, the pullout of the circuit breaker allows the computer to recover its memory. It has been fixed during the second phase of the flight program.

6. Flight Test commented that they disliked the inability to detect the second tire failure on the same axle. It is not detectable if both tires go flat at the same time.

7. Lights are not legible during sunlight. One can't tell whether the system is on or off.

8. After the modification of the computer programs, the display gives out good data statically. However, once the airplane is moving, erratic numbers are still displayed.

9. Lamp test should be combined with system test.

10. If failure occurs, light should latch on but still should be able to read other tire load.

11. Sometimes the system stays in flight mode "U04" after landing. Then it stays until another landing before the readings are being displayed again.

12. Excursions are less during landing roll than during taxi.

13. No information on increasing tire pressure.

14. Braking influences loads, it appears to throw all pressure on forward wheels, such as getting 170 and 160 on forward wheels while this does not happen in actuality.

15. From the tire deflating test data, the flat light did not come on quick enough. It either takes a longer time to come on or it is not sensitive enough to detect a flat tire at 62.5%. The test data showed that the flat light comes on at 49%.

16. During the RTO test, there were 3 tires which went flat, only W1 and W3 were indicating flat, W2 did not give out the flat signal. It showed only two flats out of three at any one time.

(4) LOW TIRE DETECTION VIA AXLE TILT (Weight and Balance System)

A. SYSTEM DESCRIPTION

This weight and balance and low tire detection system is designed to compute an airplane's gross weight, center of gravity location, and to detect low tire pressure on the main or center landing gears. The system sensors are special closed loop servo inclinometers (servo accelerometer). These sensors measure the indication of the landing gear bogie beams and the center and nose gear axles. The weight on each gear is determined by measuring the inclination which is due to bending of the axles and beams. The center of gravity is determined from the weight distribution. Low tire pressure is determined by sensing the inclination of the beam or axle which is due to non-uniform loading on the tires.

Detection of low tire pressure on the center gear is accomplished by sensing the inclination of the center gear axle. This inclination is a measure of the relative tire pressure on the two tires. The outputs of two axle mounted inclinometers which are oriented in opposite directions at the ends of the axle are subtracted, one from the other. This difference is a measure of the tilt of the axle. On a level runway, even tire pressure distribution between the two center gear tires will, theoretically result in a zero degree tilt of the center gear axle.

Similar in principle to the center gear, the main gear tire's pressure distribution can also be detected. Ten inclinometers were used to test the feasibility of the system. The location and orientation of the ten sensors is shown in Figure 30. A cockpit display was not used as the data was simply recorded on an oscillograph and FM tape for the preliminary evaluation.

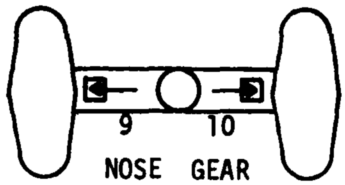
An important feature of the weight and balance and tire pressure system is its automatic zeroing capability. The sensor outputs for zero weight are determined so that sensor misalignment and bias effects can be eliminated during airplane weighing. The procedure for automatic zeroing is to filter sensor outputs during approach conditions and sense the DC levels of the sensors. This concept was successfully tested.

B. LABORATORY TEST RESULTS

Laboratory tests were conducted but the results were not significant enough to report.

C. INSTALLATION PROCEDURE

The inclinometers were modified to achieve a suitable scale factor (10 volts per g). The sensors were then attached to the mounting and electrical connectors were attached so that the sensor signals could be routed to the airplane's cabin. The installation only consumed 1/2 manhour. Typical accelerometer installations are shown in Figures 31 to 33.



NOTE: ARROWS SHOW POSITIVE ORIENTATION OF SENSORS

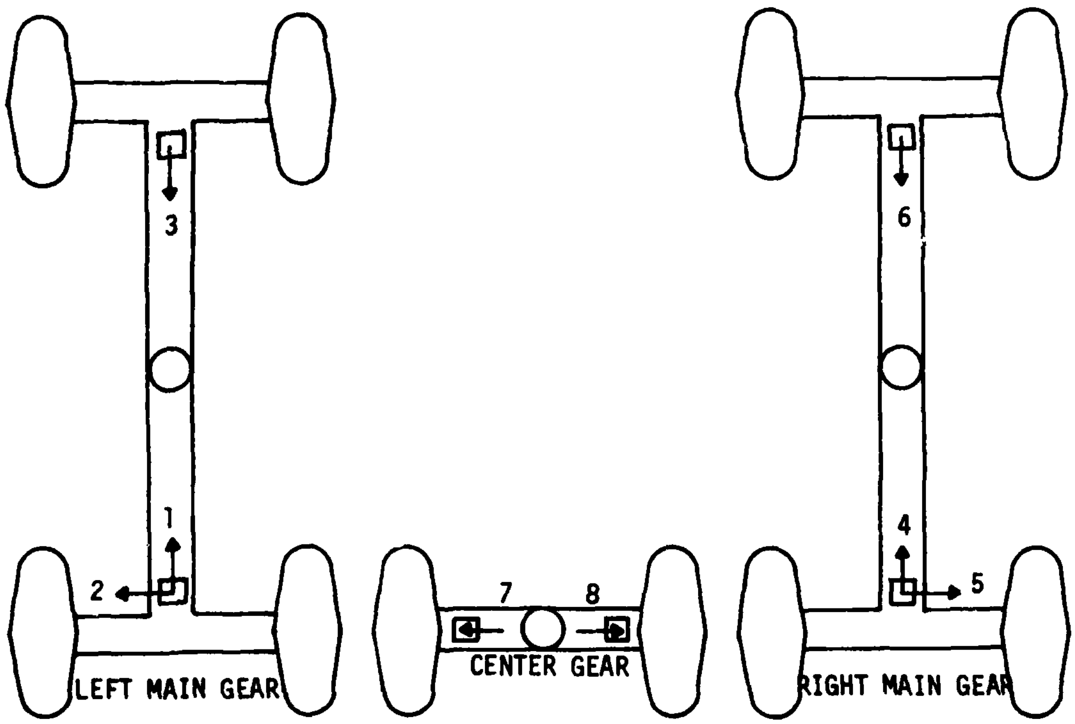


FIGURE 30

SENSOR MOUNTING LOCATIONS

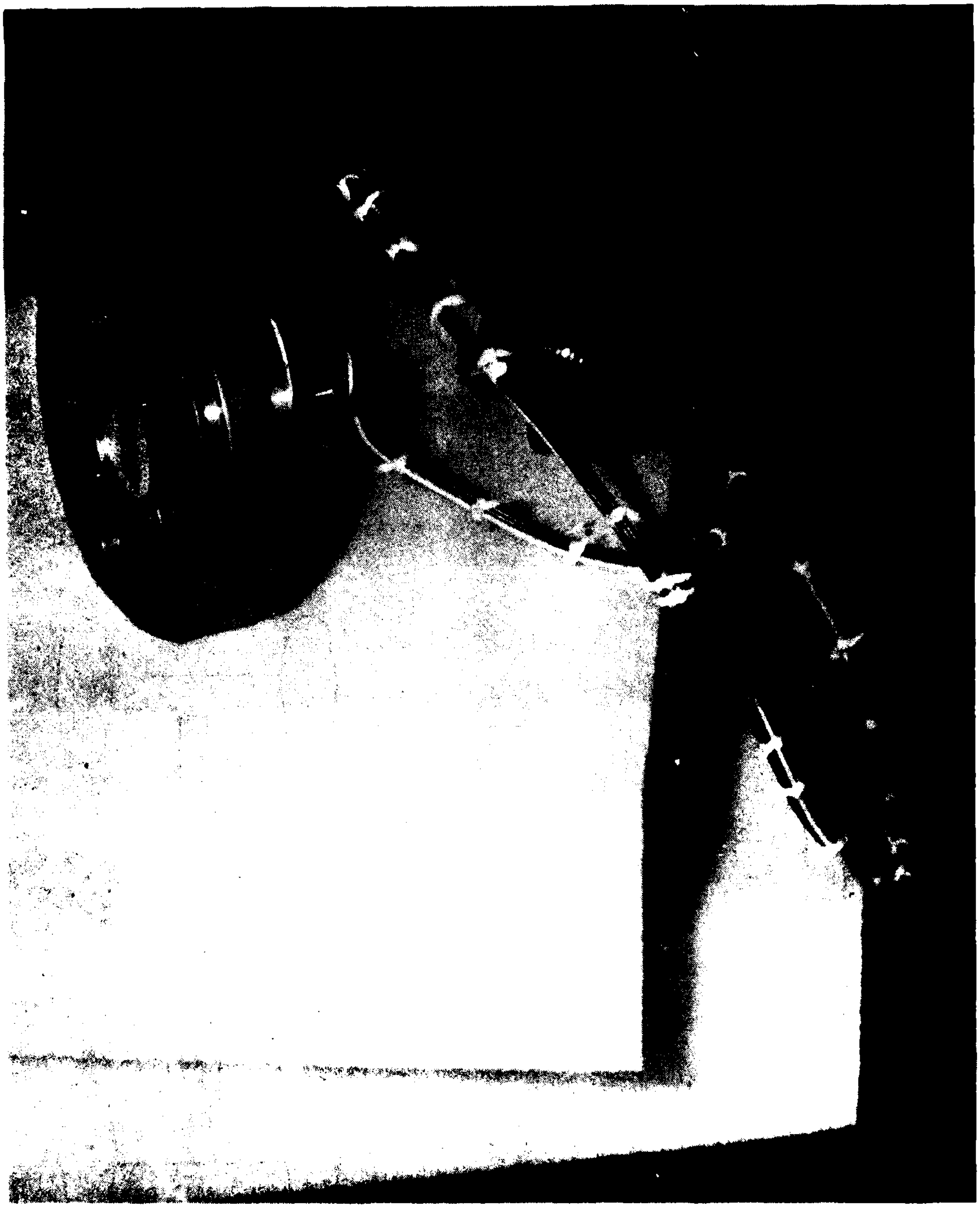


FIGURE 31. NOSE WHEEL SENSOR AND MOUNT

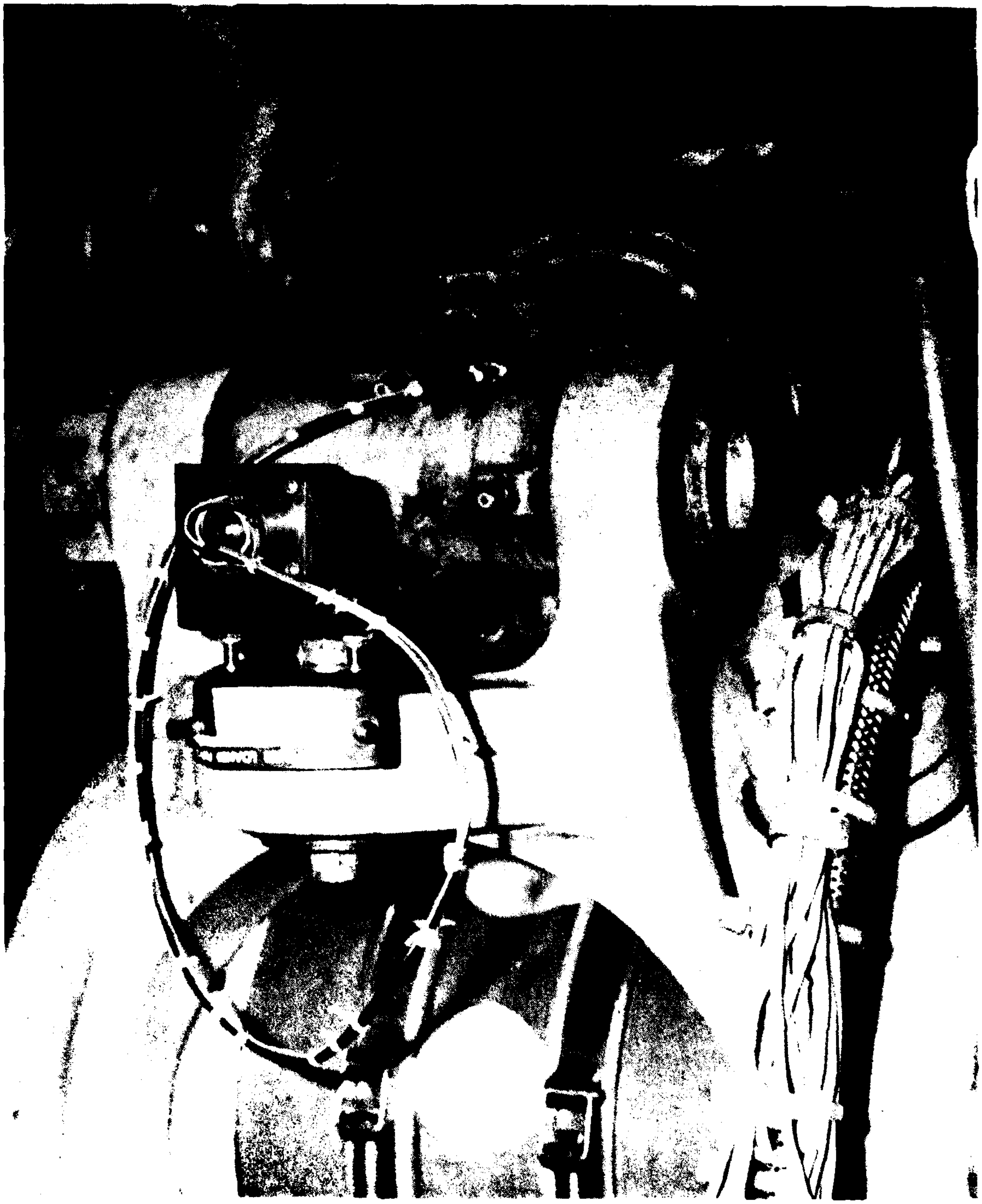


FIGURE 32. FORWARD BOGIE BEAM MOUNT AND SENSOR

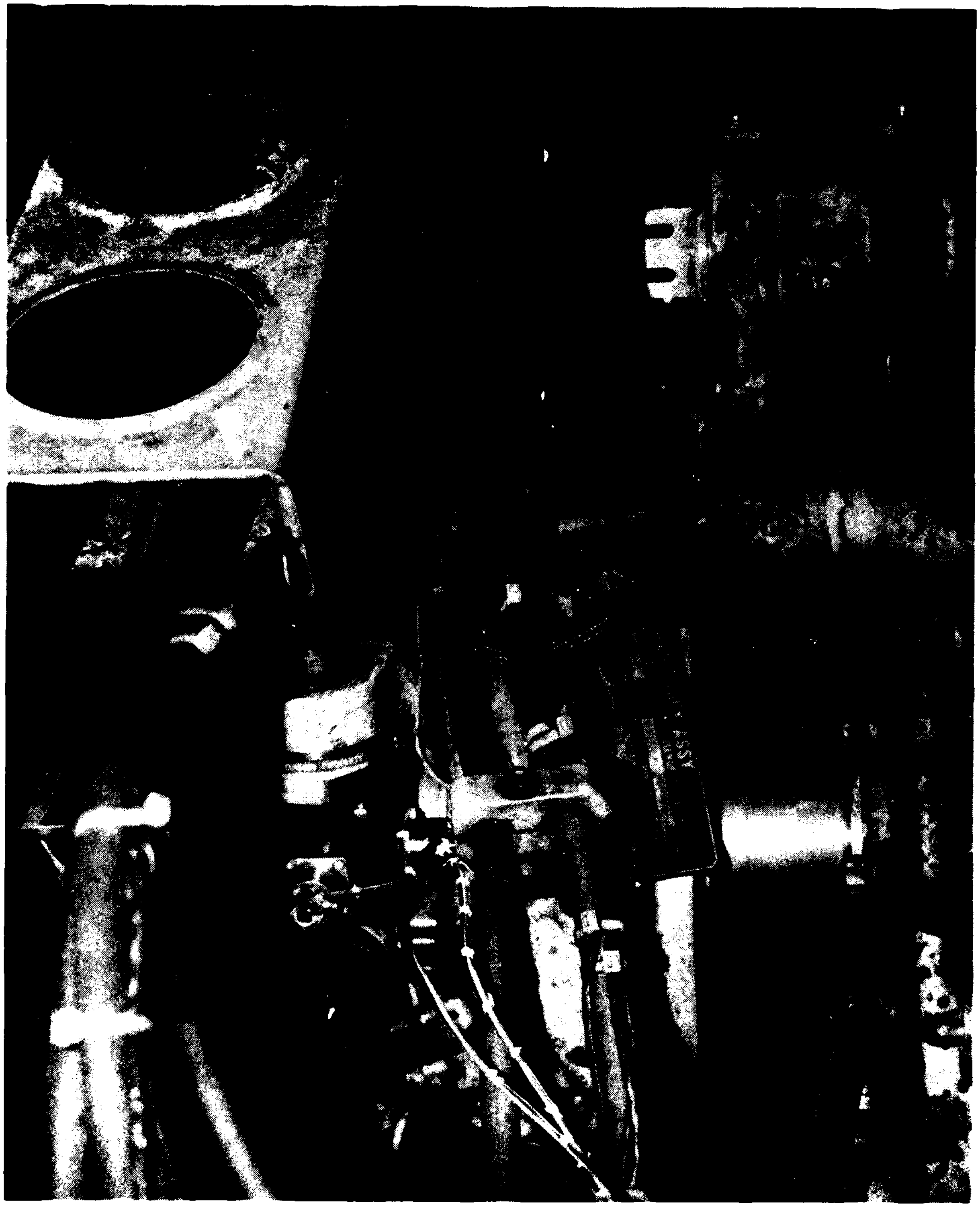


FIGURE 33. AFT BOGIE BEAM MOUNT AND SENSORS

D. FLIGHT TEST RESULTS

The servo inclinometer sensor system was tested for both static and dynamic (aircraft in motion) ability to detect underinflated tires. Low tire pressure test results are shown in Figures 34, 35, 36, and 37.

The following tires were deflated with the aircraft at rest. In steps one at a time: center gear left tire, left main gear inboard forward tire. Dynamic results ae shown in Figures 38 and 39.

Runway tilt and sensor misalignment will cause a non-zero reading. Runway tilt can be determined by combining the outputs of other inclinometers. Figure 34 shows that with the tires evenly pressurized an 0.7° tilt resulted. This angle is due to runway tilt and sensor misalignment. Each of these are detectable. Therefore low tire pressure can be determined by sensing the axle tilt angle, premeasuring the misalignment and sensing runway tilt. With this information and the characteristics curve shown in Figure 34 the relative tire pressure between the two center gear tires can be determined.

Each main gear has a bogie beam which supports two axles and four tires. Relative tire loading between the front pair and the rear pair can be determined by the bogie beam tilt. In order to determine which of the front tires or which of the rear tires are low, a lateral mounted inclinometer measures the twist of the beam in the area of the axle.

Figure 35 shows that a low tire on the front or rear of the gear will cause the bogie to tilt forward or aft. This figure shows the bogie angle for both a forward tire and a rear tire being deflated, in steps, one at a time. The other three tires, in each case are at the nominal 200 psi.

Once the tire pressure distribution between front and rear tires is determined as shown in Figure 35, the distribution between left and right tires on the front or rear is measured by sensing the torsional twist angle on the bogie beam due to left and right relative distribution. Figure 36 shows this relationship. An initial angle due to installation (about 1.5°) existed when the tire distribution was even. The inboard rear tire is deflated and a lateral inclinometer mounted near the rear tires on the bogie beam senses the twist of the beam, as shown in Figure 36. This twist angle is small, less than 0.5° for the tire pressure range explored. The angle detected by this rear mounted inclinometer was even smaller when the forward tire was deflated. (See Table VI for data.)

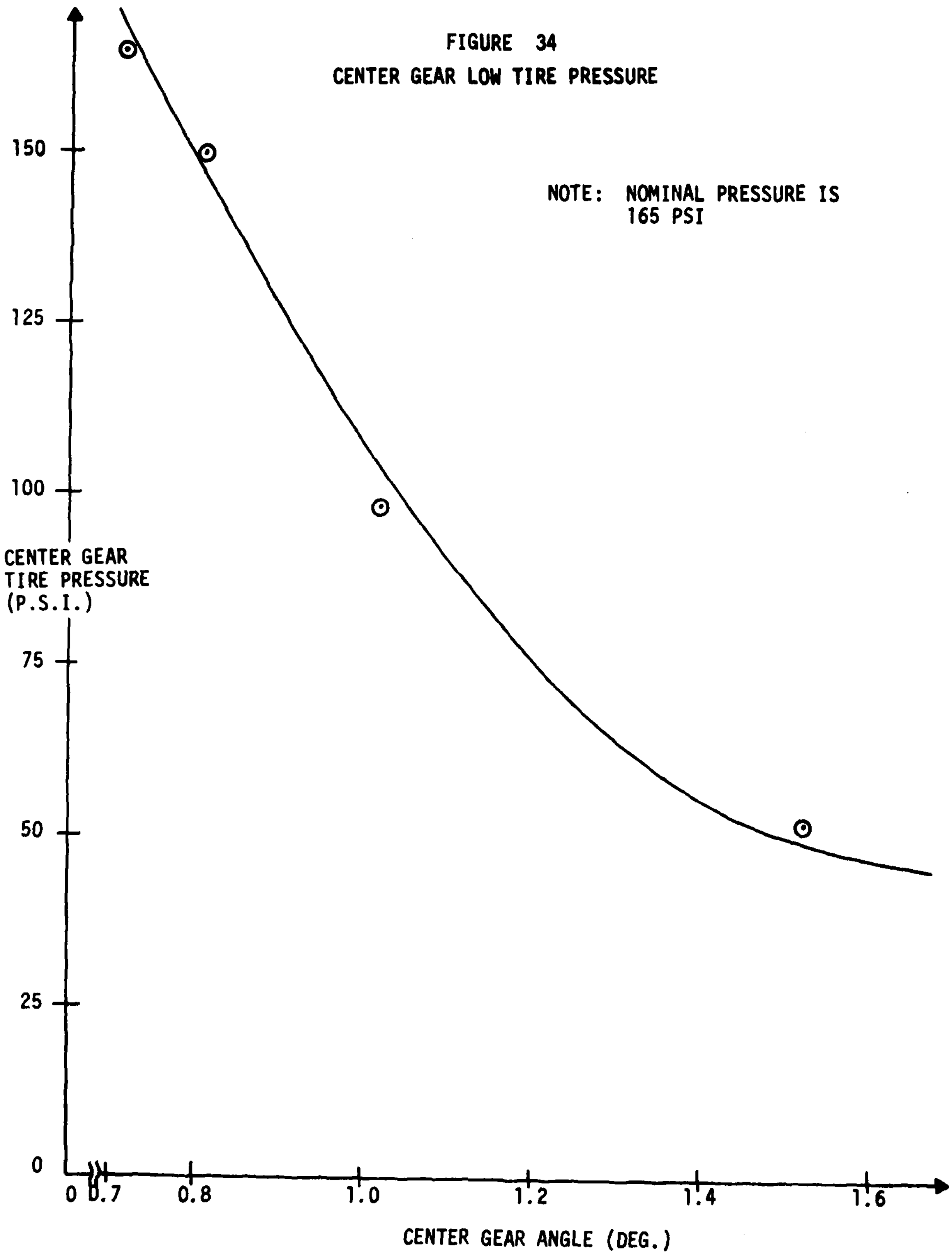


FIGURE 34
CENTER GEAR LOW TIRE PRESSURE
NOTE: NOMINAL PRESSURE IS 165 PSI
CENTER GEAR TIRE PRESSURE (P.S.I.)
150
125
100
75
50
25
0
0
0.7
0.8
1.0
1.2
1.4
1.6
CENTER GEAR ANGLE (DEG.)

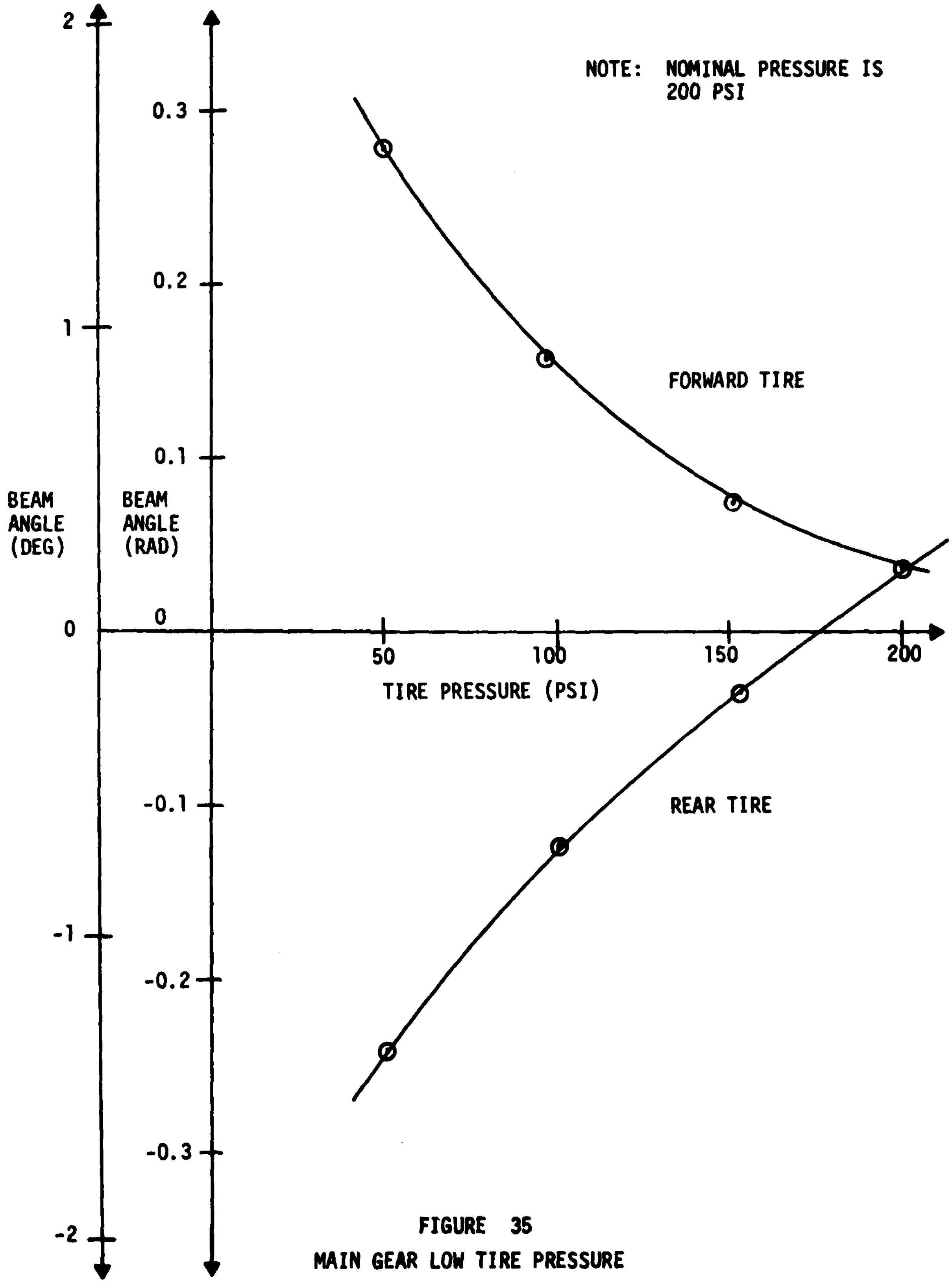


FIGURE 35
MAIN GEAR LOW TIRE PRESSURE

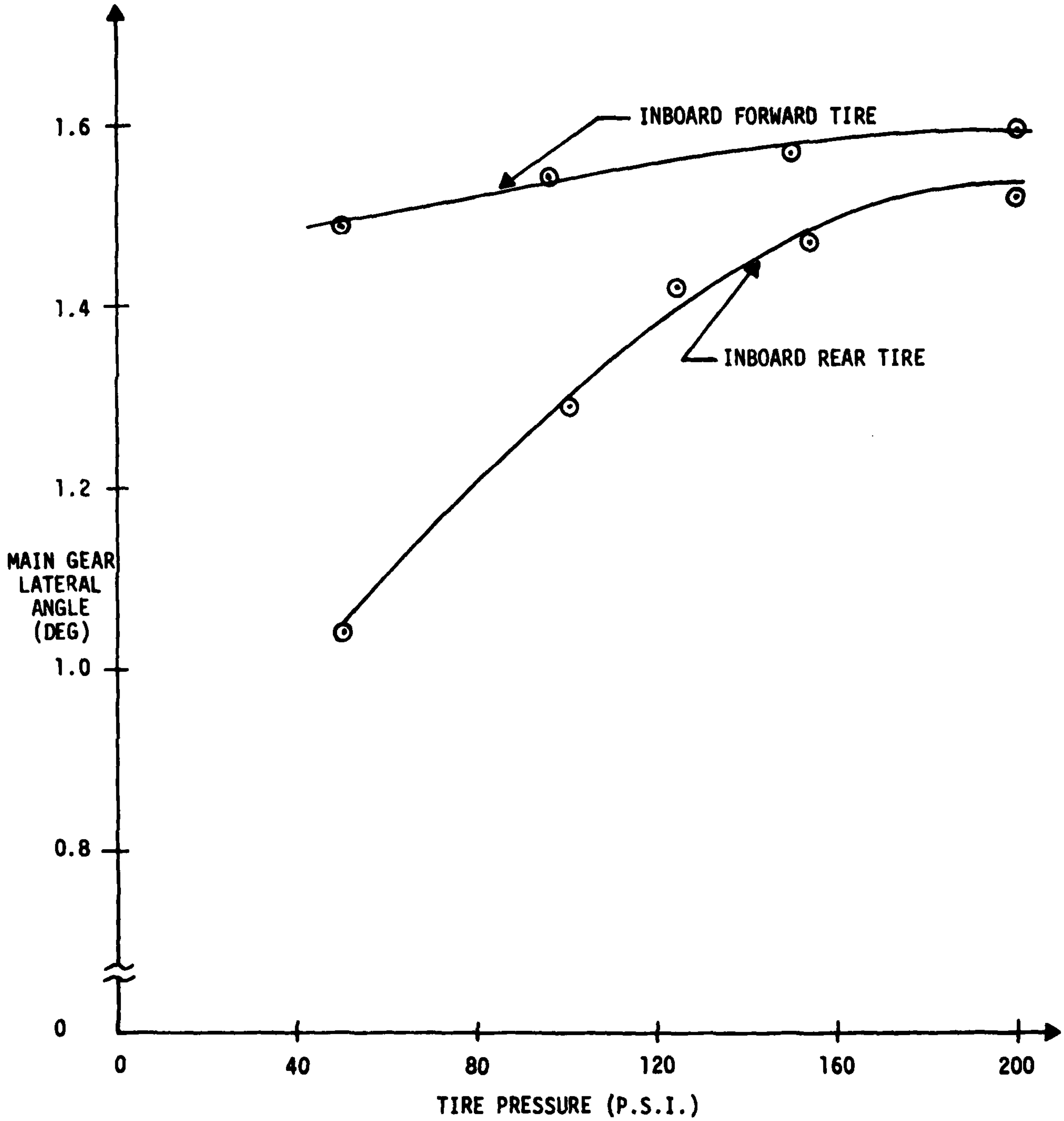


FIGURE 36
LOW TIRE PRESSURE TORSIONAL EFFECT

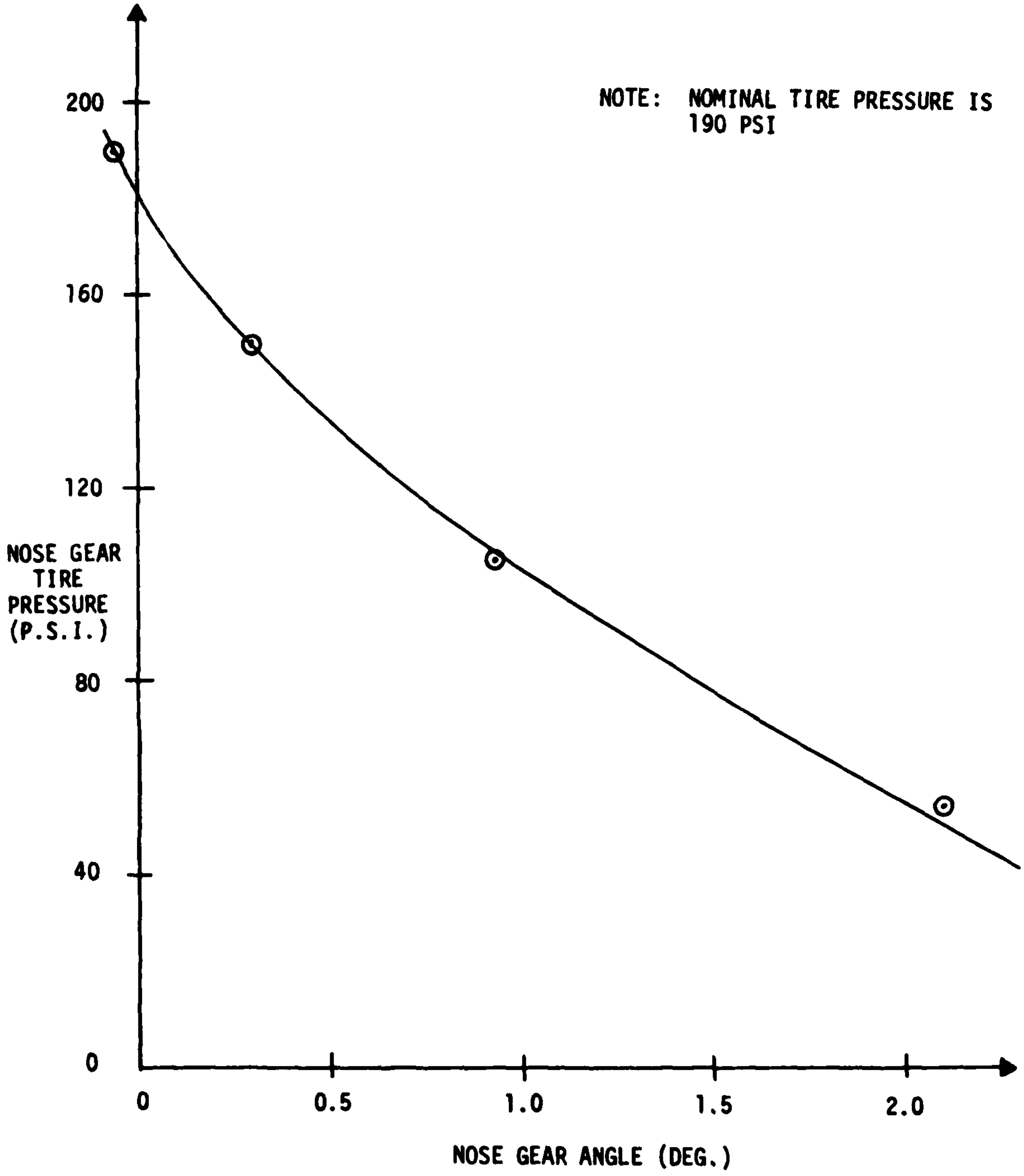


FIGURE 37

NOSE GEAR LOW TIRE PRESSURE

Nose wheel low tire pressure detection does not appear to be feasible unless the inclinometer readings can be corrected for nose wheel turn angle. The problem is that a non-zero turn angle on the nose wheel will cause a non-zero axle angle. A non-zero axle angle is, however, the same symptom used for low tire pressure detection. Therefore, unless turn angle is known, a low tire cannot be detected.

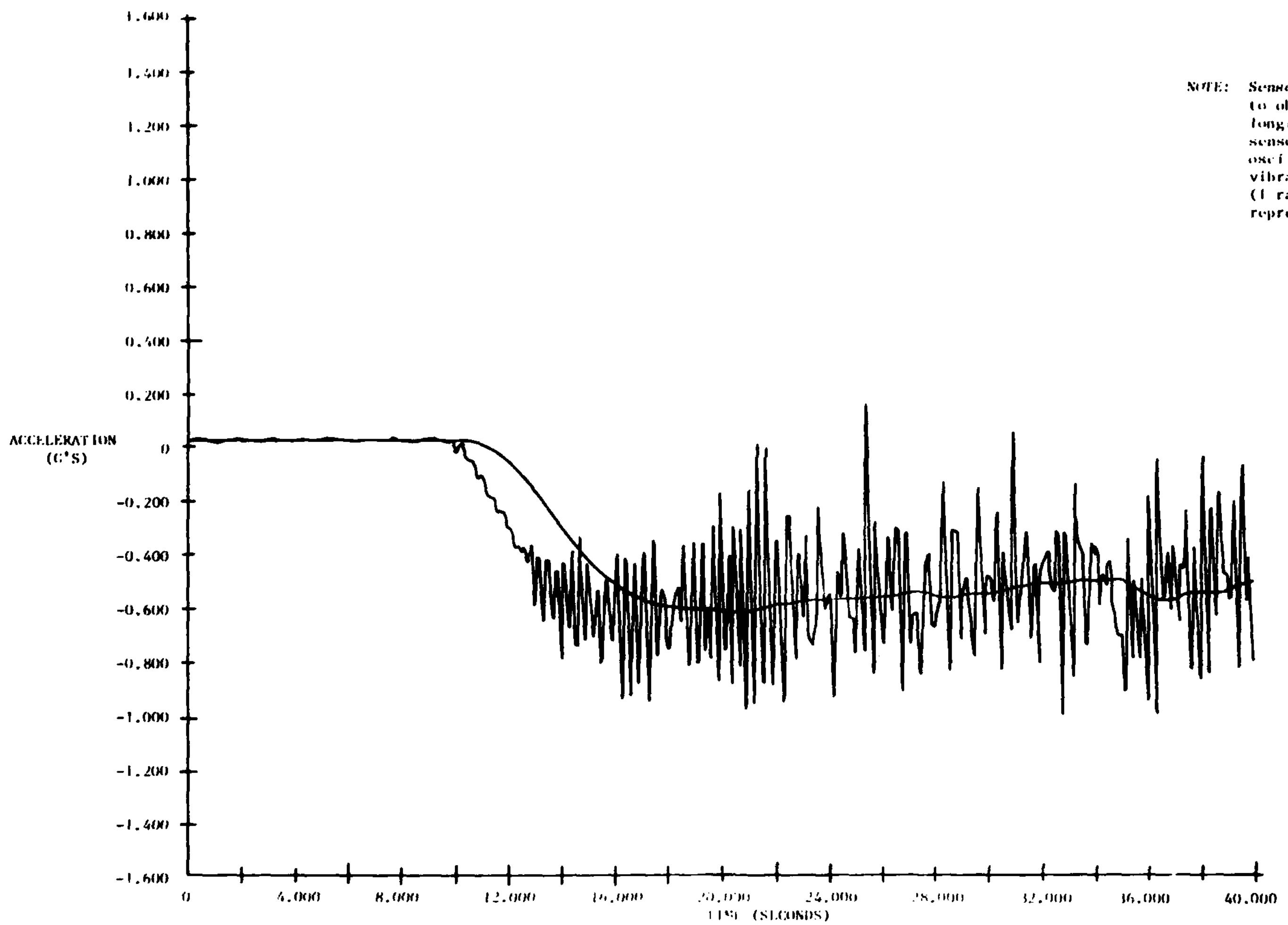
Figure 37 shows the results of low tire pressure on nose wheel axle tilt angle. As the tire pressure in the left tire is reduced to about 25% the axle tilts over 2 degrees.

Figures 38 and 39 show main gear low tire pressure detection results of the airplane in the first part of the takeoff roll. Each figure shows one 40 second segment of the takeoff roll with and without a 1 rad/sec second order digital filter applied. During the first 12 seconds, the airplane is at rest. The remaining 28 seconds show the airplane accelerating to 0.3 g's. Figure 38 displays the results of subtracting sensor number three from number one. The result is then the left bogie beam angle effect minus two times the airplane's acceleration, or about -0.6 g's.

The main gear's bogie beam will tilt about 1.5° if a tire is blown. The g effect of this tilt angle is about 0.026 g's. Since this number is small in comparison to the accelerations shown in Figure 38 another concept was explored. The angles on the left and right bogie beams were compared by subtracting one from the other.

Figure 39 shows the results of this comparison during the same 40 second segment as Figure 38. It was hoped that the beams would be at the same angle so that the filtered output would remain at zero. If this were the case, then a blown tire on one beam would cause a variation which would be detectable. However, Figure 39 indicated that the beams may be varyig in tilt angle. This variation is a low frequency phenomenon which raises questions as to whether the variation in angle is real or if perhaps the recording/filtering techniques were not precise. The plot indicates that the beam angles vary by as much as 5% with all tires fully pressurized. Further testing is therefore required to determine whether low tire detection is feasible with the aircraft in motion.

Although a very small tilt angle can be detected axle tilt is a relatively insensitive measure of the pressure. Table VI shows that a drop from 165 psi to 50 psi, or change of 0.8° is obtained. If the low tire pressure threshold is set at 130 psi, then a change of 0.2° is obtained. This angle change is obviously quite small.



NOTE: Sensor #3 is subtracted from sensor #1 to obtain beam angle effect. Airplane longitudinal data times two is also sensed. Raw data is shown by the oscillating pulse which is due to vibration and noise. Filtered data (1 rad/sec second order filter) is represented by the single solid line.

FIGURE 38

TAKEOFF RUN - DYNAMIC LOW TIRE DEFLECTION DATA

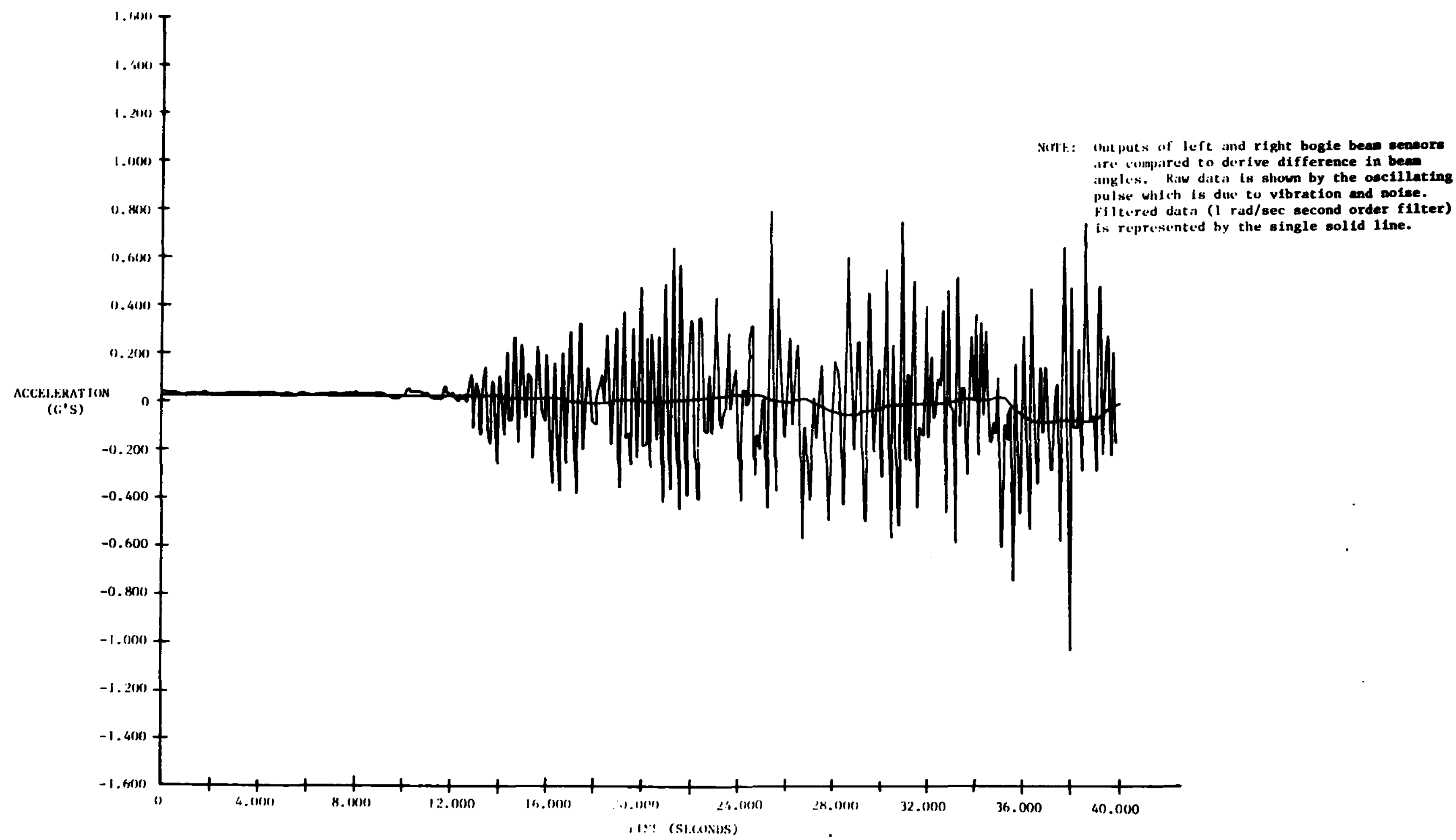


FIGURE 39

TAKEOFF ROLL - DYNAMIC LOW TIRE DETECTION DATA

Tilt angle versus tire pressure is shown on Table VII and Table VIII for left main gear and nose gear respectively. Again, the tilt angle is very small.

E. PROBLEMS ENCOUNTERED/RESOLUTIONS

During initial installation, two inclinometers were damaged during ground handling prior to installation. Another inclinometer was damaged after installation during a tire change. Airplane data was virtually all obtained statically. No usable dynamic data was obtained. Despite relative insensitivity, the system produced good results statically. Either the system will have to be limited to a static check of tire condition while stopped at the end of the runway or better means will have to be developed to detect the very small tilt angles in the large accelerations detected dynamically. Further, this system is affected by the same error budget as discussed in the "problems encountered" section for system 3 (the other weight and balance system approach which uses bogie shear instead of axle tilt).

To resolve the problem of damaged inclinometers, the basic sensors used in the inclinometer must be packaged to survive the environment, especially vibration and handling. Also, the axle mounts must be designed to reduce movement of the moment while in service.

TABLE VI

CENTER GEAR LOW TIRE PRESSURE

LEFT TIRE PRESSURE (P.S.I.)	CENTER AXLE ANGLE (DEG)
165	0.7127
150	0.8091
98	1.0198
52	1.5194

TABLE VII

LEFT MAIN GEAR TIRE PRESSURE

INBOARD FORWARD TIRE PRESSURE (P.S.I.)	INBOARD REAR TIRE PRESSURE (P.S.I.)	BOGIE PITCH ANGLE (DEG.)
200	200	0.1960
151	200	0.4105
96	200	0.8846
50	200	1.5731
200	200	0.1960
200	154	-0.2216
200	125	-0.3626
200	101	-0.7123
200	50	-1.3838

TABLE VIII

NOSE GEAR LOW TIRE PRESSURE

LEFT TIRE PRESSURE (P.S.I.)	AXLE TILT ANGLE (DEG.)
190	-0.06
150	0.29
106	0.93
54	2.10

AD-A081 598 DOUGLAS AIRCRAFT CO LONG BEACH CA F/G 1/4
FLIGHT TEST EVALUATION OF AIRBORNE TIRE PRESSURE INDICATING SYS--ETC(U)
SEP 79 R R SUITER, W W KWONG DOT-FA77WA-4070
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(5) GO-NO-GO LOW TIRE PRESSURE SYSTEM

A. SYSTEM DESCRIPTION

This prototype configuration tire pressure indicating system is a go/no-go type system which employs an automotive application concept. Tire pressure is sensed as being above or below a 140 ± 10 psi threshold by a pressure activated electrical switch which is mounted on the wheel. The information is passed through the wheel unit sensor mounted on the wheel heat shield, then into the stationary electronic module mounted on the brake housing. The signal is received once every wheel revolution. The pressure switch has been designed to operate so as to close the coil circuit at pressures above 140 psi and to open the coil circuit below 140 psi.

Tire pressure detection is functional only when the aircraft is moving at ground speeds greater than 3 knots. In the prototype configuration it was necessary to "clear" the display by pressing the reset button when the aircraft taxi speed is above 3 knots. Otherwise, the system produced erroneous indications.

System Components are as follows:

1. Wheel Unit Assembly

This assembly consists of a pressure switch and coil subassembly interconnected by a three-wire shielded cable. The pressure switch has been designed to operate at 140 ± 10 psi so as to close the coil circuit at pressures above 140 psi and to open the coil circuit below 140 psi.

The pressure switch is installed in place of a fusible plug on the wheel. The switch contains an integral Schraeder valve which functions to prevent pressure loss in the event that the pressure switch body is broken off for any reason.

The coil subassembly is mounted to the wheel rim with a bracket.

2. Stationary Electronic Module

This module contains oscillator and amplifier electronics and two sensing coils mounted in close proximity. Electrical power is supplied through an electrical connector. The oscillator oscillates when the coil contained in the wheel unit assembly is aligned with the coils contained in the Stationary Electronic Module. The momentary oscillation (burst) causes the output of the amplifier to go to a logic "1". This signal is supplied through the connector to the control box.

The Stationary Electronic Module is mounted on a bracket which is mounted under two brake tie bolts.

3. Control Box Assembly

This assembly contains the electronic circuitry required to process the tire pressure status signals from the left main landing gear wheels. Additional electronics control the cockpit display. The electronics are contained on two circuit cards contained within a LONG 3/8 ATR case. The front panel of the control box contains 9 status lights.

4. Monitor Control Assembly

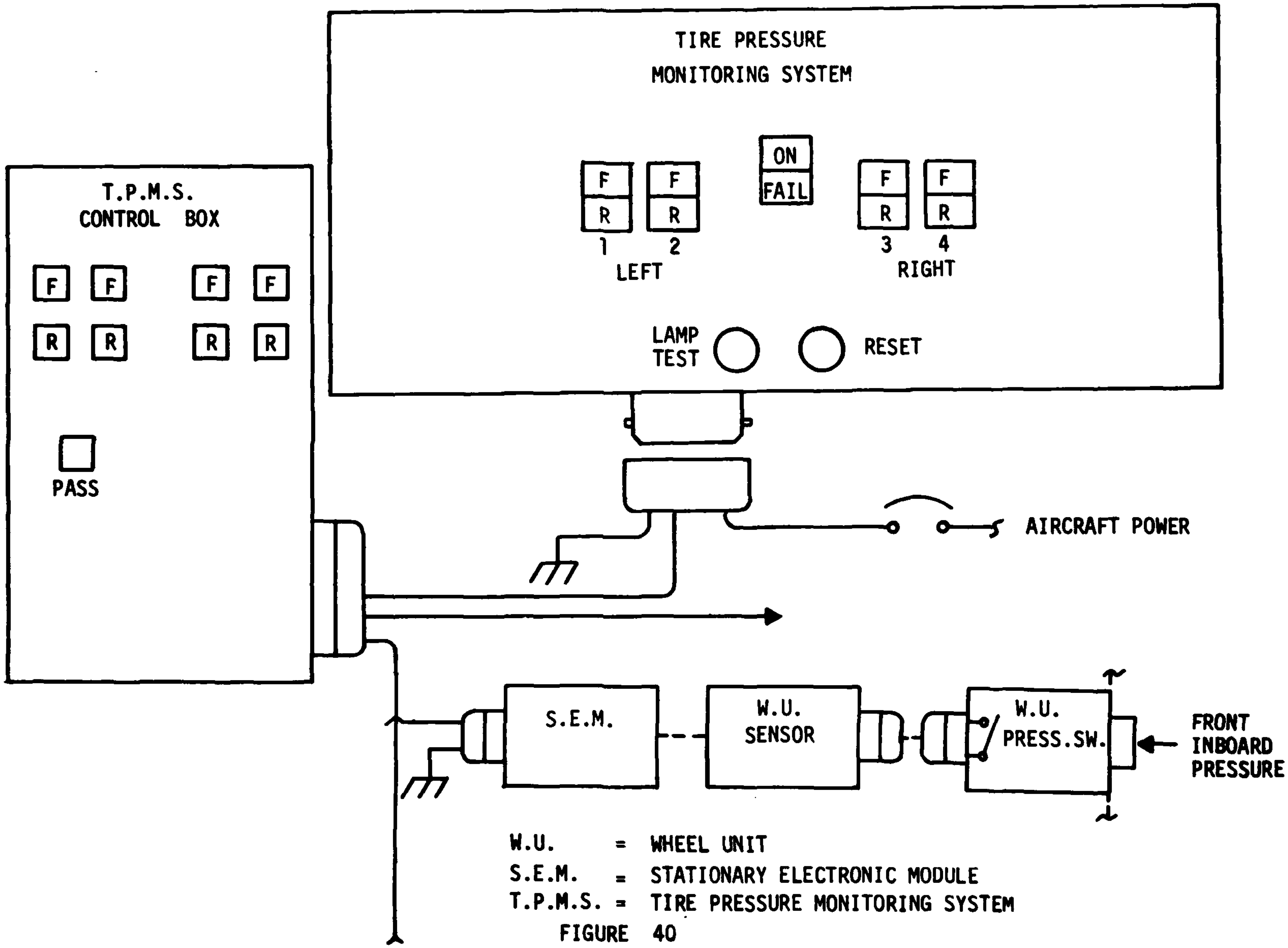
The Monitor Control Assembly is the cockpit display module shown and diagramatically in Figure 40. This module contains five (5) lighted (amber) pushbutton switches and two (2) non-illuminated pushbutton switches on an illuminated front panel.

Concept of Operation

Mounted to the brake tie bolts in close proximity to the wheel rim is the Stationary Electronic Module. It contains a special electronic oscillator and amplifier. The electronic oscillator contains two (2) coils in close proximity but which require mutual coupling to oscillate. The mutual coupling is provided by the wheel mounted coil circuit when wheel rotation results in the rotating coil being aligned with the coils in the Stationary Electronic Module (SEM). During the period of alignment, the oscillator operates and causes the amplifier in the SEM to provide a logic "1" signal indicative of acceptable tire pressure. If a tire pressure should fall below 140 ± 10 psi, the pressure switch opens the rotating coil circuit which cancels the mutual coupling for the stationary coils regardless of wheel position. Hence oscillator opration is not possible and the amplifier output goes to a logic "0".

System Operation

The "interim" configuration TPI system described herein provided reliable tire pressure status only when the aircraft is taxiing at ground speeds above 3 knots. Below this sped, erroneous indications will result on the cockpit display monitor due to the interim nature of the design. Therefore, the display must be "cleared" by pressing the RESET button on the front panel of the cockpit monitor when aircraft taxi speed is above 3 knots. During taxi, a logic signal is achieved from each of four wheels signifying tire pressure status above or below 140 psi. These signals are examined for validity by electronic logic which in turn drives a cockpit display to provide go-no-go tire pressure status to the flight crew. If tire pressure of the left main landing gear wheels is above the 140 psi warning threshold, left-hand pushbuttons 1F, 1R, 2F, and 2R will illuminate as a PASS indication. FAIL light is OFF. If a tire pressure fails below 140 psi, the corresponding PASS light goes out and the FAIL light illuminates.



W.U. = WHEEL UNIT
S.E.M. = STATIONARY ELECTRONIC MODULE
T.P.M.S. = TIRE PRESSURE MONITORING SYSTEM

FIGURE 40

GO-NO-GO LOW TIRE PRESSURE SYSTEM SCHEMATIC

Lamp logic on the Control Box front panel is reversed. Lamps 1F through 4R indicate wheel position and illuminate to indicate a FAIL condition rather than a PASS condition. If any wheel loses pressure, the corresponding FAIL lamp goes ON and the PASS lamp goes OFF.

B. LABORATORY TEST RESULTS

Dynamometer test runs were performed under different conditions as shown in Table IX. With the threshold low light set at 140 psi, the wheel was rolling at a particular speed with air being bled off from the tire. While continuing to bleed the air, the fail light on the tire pressure monitor system was checked and recorded. The fail light did come on consistently within a range of ± 7 psi, about 4.5% deviation. From the test results, the system did perform with considerable accuracy.

C. INSTALLATION OF THE GO-NO-GO SYSTEM

The installation on one gear of the DC-10 test aircraft was simple and consumed perhaps one manhour. Wheel hardware consists of pressure switch and mounting adapter installed at a fuse plug port. With the wheel sensor mounted on wheel heat shield, it revolved with the wheel rotation and picked up the tire pressure signal from the pressure switch. Two twisted, shielded wires were required from brake mounted module to the center accessory compartment control box. In addition, the cockpit control unit was mounted in the flight engineer's station. Wires were brought from the control box to the cockpit control unit.

Checkout

With the installation completed, a verification of the system was done statically on the ground with the airplane jacked up. All four tires on the left hand bogie were individually deflated below 140 psi (the pressure at which the system was assigned to indicate a failure). The tires were then turned at a rate to simulate the aircraft moving at speed greater than 3 knots. This is because the tire pressure detection is functional only when the aircraft is moving greater than 3 knots. Initially, the gap setting was not close enough to generate a signal. Thus nothing was displayed in the cockpit control unit. The gap was then made smaller such that a signal was obtained.

RUN	BRAKE CONDITION	LANDING SPEED (M.P.H.)	UNLAND SPEED (M.P.H.)	STARTING TIRE PRESSURE (P.S.I.)	FAIL LIGHT TIRE PRESSURE (P.S.I.)
1	NO WATER	220	35.8/COAST	156.0	140.0
2	NO WATER	25	0	-	-
3	WATER	220	60/COAST	179.4	*
4	WATER	220	180/COAST	156.8	138.5
5	WATER	220	200/COAST	156.0	140.2
6	WATER	220	200/COAST	156.0	140.2
7	WATER	220	200/COAST	154.4	138.7
8	WATER	220	200/COAST	151.3	137.0
9	WATER	220	200/COAST	156.0	141.8
10	WATER	220	200/COAST	152.9	137.1
11	WATER	220	200/COAST	156.0	140.2
12	WATER	220	200/COAST	151.2	133.7

* WHEEL ROLL TO A STOP BEFORE INFLATION PRESSURE WAS LOW ENOUGH TO HAVE THE FAIL LIGHT COME ON.

TABLE IX
GO-NO-GO LOW TIRE PRESSURE SYSTEM LABORATORY RESULTS

After the gap was readjusted, however, wheel #1 would not indicate a failure even though the pressure was below 140 psi. The other tires worked properly. This caused considerable confusion until it was discovered that the Electronic Module on wheel #1 was inoperative.

Later, to avoid jacking the airplane and rotating the tires to check system operation, metal plates were used to simulate the rotating target. One man was placed at each wheel (4 men) and told to rapidly move the metal plate repeatedly in front of the Stationary Electronic Module. This provides a somewhat more satisfactory means for checkout.

As a result of this installation evaluation, however, it was clear that this go-no-go system, although easy to install, was difficult to check out and difficult to determine if it was working properly. The one failure encountered was passive and would allow a valid low tire to go undetected.

D. FLIGHT TEST RESULTS

The system was mounted on the left hand main landing gear and was on the aircraft for 5 flights with various flight conditions encountered, such as taxi, takeoff, touch and go, landing, etc. During the test program, the tire pressures were adjusted daily to 175 (+0, -5) psi. Numerous fail lights were observed during taxi due to starts and stops. While retracting the gear after takeoff, the fail light would illuminate due to wheel spin-down and subsequently the fail light would have to be reset. Random failures were observed below 25 knots on all wheels at one time or another, worse at lower speeds, that is, below 10 knots. Tire pressure failure was indicated on all tires during antiskid cycling on landing. During RTO test, three of the tires on the left hand main gear deflated due to blown fuse plugs and had to be removed from the aircraft. No damage to the hardware was found after the heavy braking run. As modifications were required for the system and because of the aircraft schedule, evaluation of the tire pressure system was discontinued. This system was later modified for further testings but the flight test program ended before a retest could be accomplished.

V. CONCLUSIONS

Over twenty cockpit indicating system concepts were evaluated in Part I of this report resulting in flight testing of seven different cockpit tire pressure indicating systems. Three concepts were intensively studied and three others evaluated on Douglas DC-10 in-flight test operations. One other concept has been taxi tested on two aircraft by two airlines. The tests were successful in demonstrating the feasibility of cockpit tire pressure indicating systems and in bringing promising concepts one step closer to workable production designs. Airline service testing of each of the remaining promising concepts should be completed before introduction into airline operation. In each case this service testing is planned in the near future or is already underway.

Concept 1

The analog pressure via axle transformer (Concept D, Part I Report) worked quite well during the flight test program. The installation of the hardware, although requiring specific modification of the DC-10 axle hub area was simple and straight-forward. Analog tire pressure data was displayed with reasonable accuracy and gave the flight crew confidence in the integrity of the system. Some objection was made to the three plus second pressure update time required by this system, but this should not be considered a significant drawback. The only significant system failure occurred in a pressure transducer (see text) which should be made acceptably remote by improved quality control by the transducer manufacturer.

Concept 2a and b

The analog presssure via signal bearing and via inboard wheel coupler systems supplied by one manufacturer were not successful although some usable data was obtained for each system. Work on the inboard wheel coupler system has been discontinued. The signal bearing system did appear sufficiently promising that the manufacturer has continued laboratory development since the completion of the flight test program. A new copper on carbon journal bearing has been developed. This appears to provide good direct signal coupling while meeting the design requirements for this system. The concept requires a somewhat difficult electrical connection path from the transducer through the hub cap into the coupler and axle. It does, however, avoid wheel mountd electronics and should be accurate.

Concept 3

The percent load via bogie/axle strain system (weight and balance approach - Concept O, Part I Report) proved workable after the system software was debugged and developed to correct for tire loading changes caused by aircraft turning and sideload effects. With attention to detail software design, this approach can provide reliable indication of 30 to 50% underinflation (see text on error budget for this system). Hardware was well built and trouble-free and the system did provide accurate aircraft weight measurement (limited in this test to one main gear). Usefulness of this approach as a weight and balance system adds to its cost-effectiveness.

Concept 4

The low tire detection via axle tilt (weight and balance system) provided very good tracking of tire pressure statically (aircraft at rest). with the aircraft in motion it is doubtful that the very small axle tilt angles (on the order of 1°) can provide a false warning-free indication of even significant tire underinflation. If a tire check is done with the aircraft static after taxi prior to the start of takeoff roll the system may be workable as a tire indication system. With the servo inclinometers properly protected against handling damage, the ease of installation of the transducers and the concept's apparent workability as a weight and balance system should make it viable.

Concept 5

The go-no-go discrete pressure system did not work satisfactorily during the test program. It was susceptible to false warnings and passive (undetected) failures that would cause a low tire to be missed. The test program ended before these problems could be addressed and fixed. As the ability of this type of system to meet the most important design criteria for TPI systems was questioned, further test and development of this system has been discontinued.

Concept 6

The wheel speed monitoring system (seventh system type to be tested) (Concept N, Part I Report) has been successfully tested by two airlines. The system gave repeatable indications of 25% tire underinflation before reaching 40 knots on takeoff roll on a DC-9 and B-727. Although the tests did not evaluate worst case tire diameter mismatches, the apparent effective operation, ease of installation, and low cost of this system make it attractive.

General Summary

The detailed tradeoff analysis of these systems from an operational, reliability, weight and cost standpoint in Part I of this report is still applicable. Based on the flight tests and the analysis in Part I the following general comments may be made:

Analog Pressure Approach

The analog systems are inherently most capable of minimizing false failure warnings and undetected (passive) failures. Flight crews that have used the systems reacted favorably to display of actual tire pressure and had confidence in the integrity of the system. The systems can be used as an indication of tire problem in <u>all</u> flight conditions and can (when analog display is provided) help reduce maintenance costs associated with the now frequent tire pressure checks. The systems also represent the highest initial cost particularly when considering the probable need to mount transducers on all spare wheels. Selection of options such as one and two light displays in the cockpit in lieu of sophisticated analog display, can reduce initial cost. It can also be well argued that the combined benefits of low false warning rates and tire pressure maintenance cost reductions justify the higher initial cost when compared to other systems. This system will be used by a number of airlines for improved tire maintenance and safety.

Weight and Balance Approach

The weight and balance system approach makes sense from a cost-effectiveness standpoint as the using airline gets two valuable functions essentially for the price of one. The complication of tire load monitoring is in software, not hardware. Tire load, monitoring accuracy is limited by the number of additional variables these systems must take into account. They are further limited in that they are only useful with the aircraft on the ground (although this is certainly the most important time). The systems have difficulty with load dynamics with the aircraft in motion but at least one system has shown that this can be solved. The weight and balance approach will be attractive to some airlines as a cost-effective means of detecting significantly low tires during taxi and the beginning of the takeoff roll.

Wheel Speed Approach

By utilizing existing antiskid wheel speed transducers this sytem is certainly the least expensive and easiest to install of the low tire sensing systems. By the nature of the design it is prone to both false warnings and passive failures. Passive failurs may be partially detected by observing proper light indications during taxi turns. By reliable and simple circuit design, returns to gate due to system failures may be kept to an acceptably low level. If an airline uses one brand of tire, false warnings due to differences in tire diameters should not be a problem. Further tests are required to determine if significantly mismatched tires from different manufacturers can also be tolerated by this system. These questions will be answered by tests already in progress or planned for the near future. The simplicity of this approach will then make it attractive to a number of airlines.

Planned Development and Service Tests

An airline with operational experience that justifies the utilization of a cockpit tire pressure indicating system has a number of system types to choose from. The choice will vary between airlines depending on particular experience and objectives or requirements for such systems. Before any system is finally selected by an airline it is strongly recommended that the following planned service and development tests be completed:

Concept 1 Analog pressure via axle transformer

Service tests are planned to start early in 1980 on two DC-10's by two different airlines. Flight test is also probable on the B-747. Nose tire installation has not yet been developed and tested which can be accomplished during in-service evaluation. System accuracy must be proven in-service. Unless ± 5 to ± 6 psi accuracy can be shown the use of analog systems in tire maintenance programs may be questioned.

Concept 2 Analog pressure via signal bearing

Service test of this system is planned to start in late 1979 conducted by one airline on a DC-10. Development test of this system is also planned on a DC-9-80 during flight test. These tests are required to prove the viability and accuracy of the signal bearing system. A suitable nose wheel installation design has not yet been completed and must be proven during in-service tests.

Concept 3 Percent tire load via bogie/axle strain

This concept is installed on an L1011 for complete flight test evaluation. An in-service test is being negotiated on a DC-10 subject to the completion of the in-axle transducer mount design required on the nose and centerline gear.

Concept 4 Low tire detection via axle tilt

This system is being installed on a DC-10 for in-service testing beginning late fall 1979.

Concept 6 Wheel Speed

The wheel speed system is being installed by one airline on ten DC-9's for a complete service evaluation beginning fall 1979. Other installations are also planned. Douglas will conduct a complete flight test analysis of the effective change in rolling radius of tires on a DC-10 with tires mismatched in size and manufacturer as well as inflation pressure. These tests may be conducted as early as fall 1979.

At the completion of these tests the systems should be developed sufficiently for relatively trouble-free introduction into airline service.

APPENDIX A

Airline Test of Wheel Speed Sensing System (Concept N, Part I Report)

Douglas personnel participated in and observed taxi tests on a DC-9-30 aircraft which had a prototype wheel speed based pressure monitoring system installed specifically for the scheduled tests. The taxi tests were conducted on May 5, 1979 by a U.S. airline.

Test Installation and Operation

The test installation consisted of one tire pressure monitor control unit, one auxiliary test box, one battery operated dual channel brush recorder, one battery operated oscilloscope, one pilot's red alarm light, and the test wire harness. The control unit, auxiliary test box, brush recorder, and oscilloscope were placed on an existing table in the forward cabin. The bracket containing the pilot's red alarm light was clamped to the underside of the glareshield just to the right of the captain. The auxiliary test box has a magnetically held "power on" switch, a "power on" light, and a red "tire pressure low" indicator light which paralleled the captain's red indicator light. The wire harness picked up antiskid transducer output signals and 28 VDC antiskid system control power. The transducer high-low signal wiring was twisted and shielded with the shields tied together and grounded at the terminal block and floating at the connector which is installed in the control unit. A dual trace "Brush" recorder displayed and recorded the difference in paired wheel speeds and aircraft speed in knots (based on transducer frequency).

The operating principle is based on comparing the frequency of the square wave outputs of the antiskid wheel speed transducers. The rolling radius of tires (wheel speed) vary with inflation pressure. In this test, the two outboard wheels (#1 and #4) are compared and the two inboard wheels (#2 and #3) are compared. The system is designed to turn itself off when aircraft speed reaches approximately 50 knots by releasing the magnetically held pushbutton. In addition, testing the antiskid system automatically tests the tire pressure monitor system.

System Evaluation - Taxi Test

The aircraft was equipped with the following four B.F. Goodrich tires which were inflated to 165 psi. The measurement of the vernier height readings from pavement to inner surface of the wheel rim was recorded.

- Tire #1 New retread, R9. Measured height was 10.104 in.
- Tire #2 Worn - replacement condition, R2. Tread depth < 1/32 in. Measured height was 9.702 in.
- Tire #3 Approximately 50% worn, R1. Traced depth 9/64 in. Measured height was 9.857 in.
- Tire #4 Approximately 80% worn, R2. Tread depth 3/32 in. Measured height was 10.052 in.

Taxi Test #1 (0% Underinflation)

Aircraft taxied in a straight line and the "Brush" recorder trace verified Number 1 and 4 wheel speed were equal with trace in center of paper. Aircraft speed trace also indicated aircraft speed in knots. When the aircraft was making hard turns of approximately 30 degrees or more, the "tire pressure low" light came on and remained on. This is a form of self-test that verifies the system is operating. The aircraft was lined up on the runway for a simulated takeoff, brakes were released and takeoff power applied. The "tire pressure low" light came on momentarily at power application. The differential speed trace on the Brush recorder spiked momentarily to full scale differential speed and returned to the zero differential (the center scale). At 46 knots, no further light indication displayed and the system turned itself off. (Magnetically held pushbutton released and "power on" light went out.) Takeoff run was aborted. When aircraft speed was somewhere below the 46 knots disarm speed, the "power on" pushbutton was depressed and the system activated for the taxi back to the maintenance ramp area. When the aircraft was braked to a stop, the "tire pressure low" light again came on momentarily. The differential speed trace on the Brush recorder again spiked momentarily to full scale differential speed and returned to zero. All data are shown in Table A-1.

Taxi Test #2 (13.5% Underinflation)

After the first taxi test, tire pressure increased as given in Table A-1. With test #2, proceeded immediately after test #1, tire pressures remained the same as it was just measured after test #1 with the exception of tire number 1. The pressure of that particular tire was being reduced to 160 psi which made tire #1 to be 13.5% underinflated as compared to tire #4. Taxiing and takeoff run was conducted similar to the first test. Indications appeared the same as in the first test including automatic turn-off at 46 knots. There was no indication of a low tire when aircraft was taxiing in a straight line or in the simulated takeoff run. All data are shown in Table A-1.

Taxi Test #3 (25.6% Underinflation)

Tire #1 pressure was reduced to 145 psi and all other tires were left at measures just measured. This pressure reduction created a 25.6% underinflation. Taxiing and takeoff run was conducted similar to test #1 and all indications appeared as in test #1 except the "tire pressure low" light came on at 35 knots during the simulated takeoff run and remained on. There were no brakes applied at the time of takeoff power application during this test which discounted any antiskid or brake cycling as a source of the continued momentary illumination of the "tire pressure low" light at takeoff power application and final braking stop. All data are shown in Table A-1.

Taxi Test #4 (26.8% Underinflation)

Tire #2 pressure was reduced to 150 psi and all other tires were inflated to 205 psi. A 26.8% underinflation was created between tire #2 and #3. Taxiing and takeoff run was conducted similar to test #3 and all indications appeared as in test #3 including a steady illumination of the "tire pressure low" light when reaching 35 knots. Brakes on the right hand gear were starting to smoke at this time. All data are shown in Table A-1.

Taxi Test #5 (50% Underinflation)

Tire #1 pressure was reduced to 110 psi and all other tires inflated to 220 psi. Thus, a 50% underinflation was created between tire #1 and #4. At 15 knots after taxiing started, the "tire pressure low" light came on and remained on. All data are shown in Table A-1.

Summary

The system seemed to perform satisfactorily while detecting 25% or greater underinflation. The "tire pressure low" light came on while turning which was considered by the airline to be a good "self-test" feature. Other false warnings encountered at the stop, although not resolved at the time of test, should be able to be eliminated. (See Part I Report for discussion of this system from false warning standpoint.)

The key concern about this system (discussed in detail in Appendix B) is possible false warnings due to "normal" variations in tire rolling radius. All tires used in this test were of relatively nominal dimensions and were made by one tire manufacturer. A test with worst case tire dimensions would increase certainty of the viability of the system.

TABLE A-I

WHEEL SPEED LOW TIRE DETECTOR TEST

1. PRIOR TO FIRST RUN:

TIRE NO.	PRESSURE	RADIUS
1	165	10.104
2	165	9.702
3	165	9.857
4	165	10.052

1A. AFTER FIRST RUN:

TIRE NO.	PRESSURE	RADIUS
1	190	9.824
2	195	-0-
3	189	10.080
4	185	9.983

2. PRIOR TO 2ND RUN:

TIRE NO.	PRESSURE	RADIUS
1	160	9.670
2	195	-0-
3	189	10.080
4	185	9.983

2A. AFTER 2ND RUN:

TIRE NO.	PRESSURE	RADIUS
1	175	-0-
2	208	-0-
3	200	-0-
4	195	-0-

3. PRIOR TO 3RD RUN:

TIRE NO.	PRESSURE	RADIUS
1	145	9.651
2	208	9.885
3	200	-0-
4	195	-0-

3A. AFTER 3RD RUN:

TIRE NO.	PRESSURE	RADIUS
1	150	-0-
2	210	-0-
3	205	8.998
4	205	10.173

4. PRIOR TO 4TH RUN:

TIRE NO.	PRESSURE	RADIUS
1	205	9.655
2	150	9.875
3	205	-0-
4	205	-0-

4A. AFTER 4TH RUN:

TIRE NO.	PRESSURE	RADIUS
1	215	-0-
2	165	-0-
3	220	-0-
4	218	-0-

5. PRIOR TO 5TH RUN:

TIRE NO.	PRESSURE	RADIUS
1	110	9.325
2	220	9.736
3	220	-0-
4	220	-0-

5A. AFTER 5TH RUN:

TIRE NO.	PRESSURE	RADIUS
1	118	-0-
2	222	-0-
3	220	-0-
4	220	-0-

"-0-" INDICATES THAT THE VERNIER HEIGHT READINGS WERE NOT OBSERVED.

Appendix B

Rolling Radius Comparison as pertaining to Wheel Speed Low Tire Detector and other Indirect means of Monitoring Tire Pressure, i.e. weight and balance and axle tilt

This concept detects an underinflated tire by comparing the rolling speeds (antiskid transducer signal) of two tires. A differential speed exceeding a preset threshold is interpreted as resulting from an underinflated tire on the faster wheel. To avoid false warning signals, the threshold differential must exceed the differential speed that results from variations in the rolling radius of tires inflated to normal, or acceptable pressures. The question addressed here is what is the normal variation in rolling or static radius with different manufacturers or different tire sizes.

Unfortunately, the effective rolling radius of the tire is not known. This could be determined by making simultaneous measurements of airplane ground speed and antiskid transducer output, but this has never been done. The actual effective rolling radius, however, is of no significant importance for this study, provided that the relationship between it and the static loaded radius is reasonably uniform. According to NASA Report TR-64, there is a fairly constant relationship that can be described by

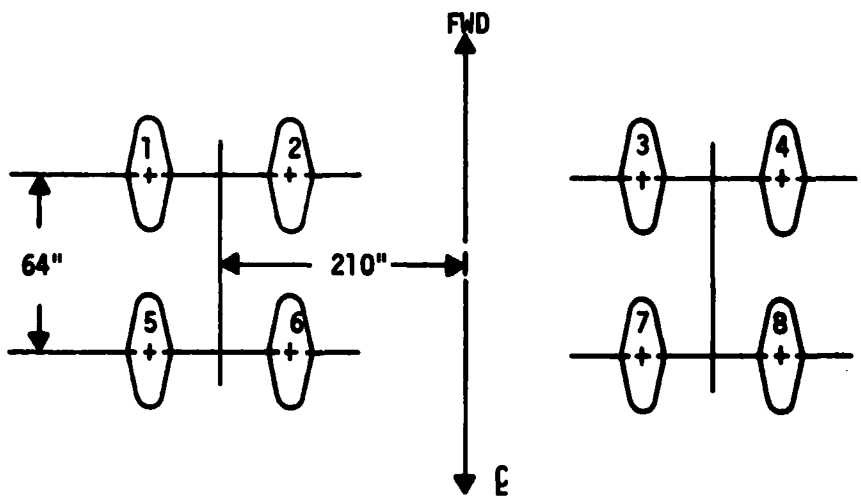
$$\text{Effective Rolling Radius} = \frac{D}{2} - \frac{\delta}{3}$$

$$\text{and } \delta = \frac{D}{2} - r_s$$

Where D = Outside free diameter of tire
δ = Vertical tire deflection for pure vertical loading conditions
r_s = Static loaded radius.

So we are concerned with the static loaded radius which can be determined.

Let's identify the wheel positions for a four wheel bogie, two main gear aircraft as follows:



Assumptions

(1) The forward and aft axles are equally loaded. For unbraked rolling, this is true for the example aircraft except for the bogie trim cylinder load, which can be a few hundred pounds in either direction, and friction in the joints, which can be in the order of $\pm$ 1,000 pounds.

(2) To avoid problems due to runway drainage crown, 0 to 1.5% slope (0 to 0.81 inch across 54 inches), the wheel speed will be compared between pairs of wheels as

1-5	3-7
2-6	4-8

which also avoids speed differential during taxi turns.

(3) Tire characteristics considered here are adverse but do not include the most extreme conditions that might occur.

- The "normal" tire is a new tire with O.D. = 49.3 inches and W = 19.1 inches.

- The "large" tire is made to maximum new tire tolerances 50.0 X 20.0 plus 2/3 of T&RA growth minus 0.08 inch of tread wear.

$$\text{O.D.} = (51.2 - 0.16) \text{ in.}$$

$$= 51.04 \text{ in.}$$

$$\text{Radius} = \frac{\text{O.D.}}{2} = 25.2 \text{ in.}$$

$$W = 20.53 \text{ in.}$$

- The "small" tire is made to minimum new tire dimensions plus 0.50 in. diameter growth minus 0.34 inch of tread wear.

$$\text{O.D.} = (49.50 - 0.68) \text{ in.}$$

$$= 48.82 \text{ in.}$$

$$\text{Radius} = \frac{\text{O.D.}}{2} = 24.41 \text{ in.}$$

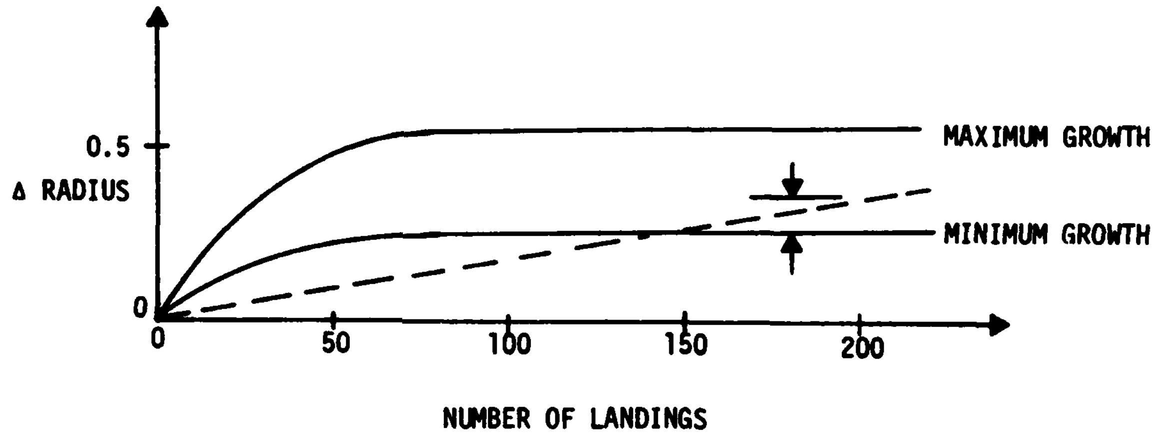
$$W = 19.26 \text{ in.}$$

- Gear Deflection. The combination of axle bending plus bogie beam torsion results in an effective spring rate of $k = 17.45 \times 10^{-6}$ inches per pound of differential load between paired wheels.

- Growth. Consideration of 2/3 of T&RA allowance.

$$\text{Width} = 2/3 \times 0.04 \times 20 = 0.53 \text{ in.}$$
$$\text{Diameter} = 2/3 \times 0.058\ (50-20) = 1.17 \text{ in.}$$

o Tread Wear. Groove depth on new tire is 0.34, but these tires are retreaded with groove depths up to 0.47 in. For the sake of study, we assume wear to 0.34 in 200 landings.



Conclusion is to assume "large" tire has 0.53 radial growth minus 0.08 wear and "small" tire has 0.25 radial growth minus 0.34 wear.

o Airplane Weight. The gross weight and center of gravity (c.g.) for a typical heavy weight for our example airplane might be

Gross weight	= 429,675 lbs.
Center of gravity	= 21.5% MAC
Load per axle	= 97,920 lbs.

At low gross weights the radius differentials will be smaller, so low weights are less critical with respect to "false" warnings.

o Tire pressures for different cases.

(a) "Normal" cases

- for "nominal" and "large" tires, tire pressure is at 180 psi unloaded (186 psi loaded).

- for "small" tires, tire pressure is at 165 psi unloaded (175 psi loaded).

That is, we will accept a warning light if the "small" tire is down to 165 psi.

(b) "Abnormal" cases

- for "small" tires, tire pressure is at 170 psi unloaded (181 psi loaded).

- for "large" tires, tire pressure is at 120 psi unloaded (125 psi loaded).

That is, we want a warning light if the "large" tire is down to 120 psi, but may have to look at 90 psi for large mating tire with tire pressure of 180 psi unloaded (186 psi loaded).

o Tire positions versus tire pressure cases.

(a) Nominal case - "Nominal" tires in all positions are at 180 psi. This case is probably not interesting.

(b) Normal case - Position "small" tire on #1 at 165 psi, "small" tire on #2 at 170 psi, "large" tires on #5 and #6 at 180 psi.

(c) Abnormal case - Position "large" tire on #1 at 120 psi, "large" tire on #2 at 180 psi, "small" tires on #5 and #6 at 170 psi.

The comparison on Table B-1 shows that the effects of variations in tire dimensions and load-deflection characteristics are such that the rolling radius of a dangerously underinflated tire can be larger than the rolling radius of a normally inflated tire on another axle. It appears that this problem could only be avoided by persuading the airline operators to refrain from installing mismatched tires. This suggestion, however, is difficult to implement.

The conditions considered for this comparison are adverse, but do not include the most extreme conditions that might occur. The extreme range of manufacturing tolerances is included, and the tires chosen probably represent the extreme range that could be expected in load-deflection characteristics. The study does not include any variables that might arise from matching new tires with retreaded tires. The study assumes that tire growth will fall between 1/3 and 2/3 of the allowance recommended by the Tire and Rim Association. The variation in rolling radius due to tread wear could easily exceed the value used here, especially for retreads, which frequently have thicker treads than new tires.

It is concluded from this study that the effects on tire static and rolling radius due to manufacturng and other tolerances are significant enough that they must be considered in any system design that monitors the effect of tire pressures indirectly. Ideally development testing of such systems (weight and balance, axle tilt, wheel speed) would include tests with worst case tire sizes to verify or refute the problems anticipated by this analysis. This was not done during the flight test program described herein but may be done as part of further testing planned by Douglas and interested airlines.

CASE	WHEEL POSITION	TIRE SIZE	UNLOAD PRESSURE (P.S.I.)	UNLOAD RADIUS (IN)	TIRE LOAD (LB)	DEFLATION (IN)	STATIC RADIUS			ROLLING RADIUS		
							r_S (in)	Δr_S (in)	$\frac{r_{S1}}{r_{S5}}$	r_R (in)	Δr_R (in)	$\frac{r_{R1}}{r_{R5}}$
NOMINAL	1	N	180	24.65	48,960	3.66	20.99	0	1.000	23.43	0	1.00
	2	N	180	24.65	48,960	3.66	20.99	0	-	23.43	0	-
	5 & 6	N	180	24.65	48,960	3.66	20.99	0	-	23.43	0	-
NORMAL	1	S	165	24.41	48,469	4.37	20.04	1.94	0.912	22.95	1.39	0.943
	2	S	170	24.41	49,451	4.35	20.06	1.92	-	22.96	1.38	-
	5 & 6	L	180	25.52	48,960	3.56	21.98	0	-	24.34	0	-
ABNORMAL (A)	1	L	120	25.52	42,237	4.16	21.36	-1.26	1.063	24.13	-1.16	1.051
	2	L	180	25.52	55,683	3.93	21.59	-1.49	-	24.21	-1.24	-
	5 & 6	S	170	24.41	48,960	4.31	20.10	0	-	22.97	0	-
ABNORMAL (B)	1	L	90	25.52	37,590	4.60	20.92	-0.82	1.041	23.99	-1.02	1.044
	2	L	180	25.52	60,330	4.20	21.32	-1.22	-	24.12	-1.15	-
	5 & 6	S	170	24.41	48,960	4.31	20.10	0	-	22.97	0	-

TABLE B-I

MAIN GEAR ROLLING RADIUS COMPARISON

NOTE: N = NORMAL TIRE
S = SMALL TIRE
L = LARGE TIRE
r_S = STATIC RADIUS
r_R = ROLLING RADIUS